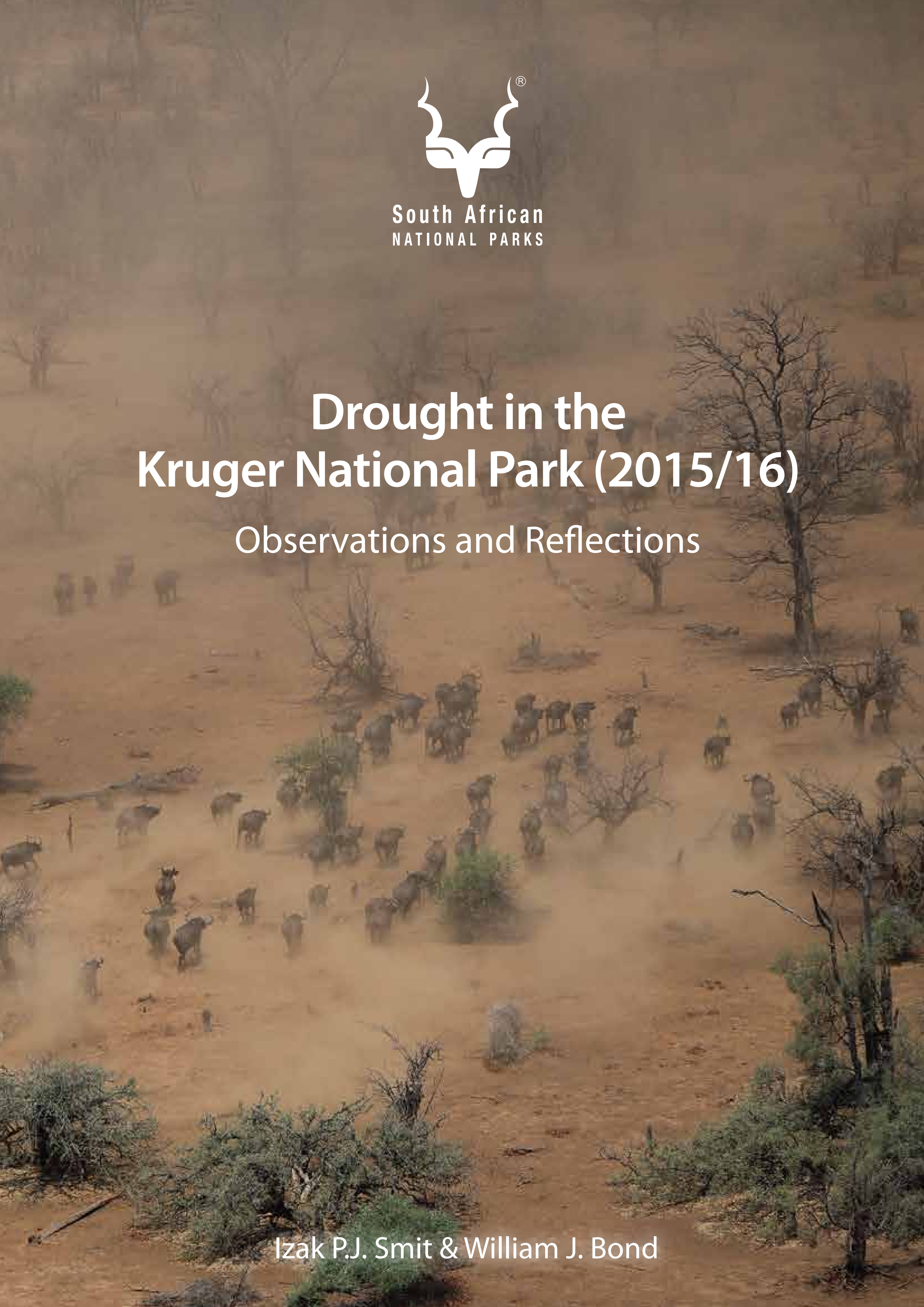

South African
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Drought in the Kruger National Park (2015/16)

Observations and Reflections

Izak P.J. Smit & William J. Bond

South African
NATIONAL PARKS

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Cover photo: Buffalo herd in Kruger National Park during drought (photo credit: Rudi van Aarde)
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INTRODUCTION TO REPORT AND HOW TO USE IT

This report summarises observations and perceptions regarding the 2015/16 drought as well as the post-drought responses, which was collected and collated from more than 50 people living and/or working within the Kruger National Park (KNP) and surrounding areas. To compliment this, more than 160 photographs are used to richly illustrate and in some cases substantiate the observations, and to act as an archive and reminder of the visible effects of the drought, as well as the post-drought responses.

Data was collected by requesting colleagues that lived and/or worked in the KNP and surrounding areas to provide feedback and photos of their observations and experiences during the 2015/16 drought and the years directly thereafter. The collated information was sorted and analysed into three levels of increasing synthesis and abstraction:

- Level 1 – **Verbatim narratives:** Raw narratives as provided by respondents (not included in this report)
- Level 2- **Cleaned and structured summary of observations:** Raw narratives from level 1 above were cleaned, combined and thematically summarised, but still retaining a high level of detail (e.g. locational information). This information is contained in Section A of this report.
- Level 3 – **Key generalizations:** Key generalizations were extracted from level 2 above. These generalizations focused on identifying consistent and/or pertinent observations. This level of abstraction included some interpretation, integration and synthesis from level 2 observations and is contained in Section B of this report. Section B is a copy of an article that will be published in 2020 in the *African Journal of Range and Forage Science* as part of a Special Issue (Volume 37) on the 2015/16 drought in the summer rainfall areas of South Africa (Smit & Bond, 2020).

It is anticipated that Section B of the report, which acts more as a summary and focuses on key generalisations and pertinent observations, will provide a good and systemic overview of the drought and will be of interest to a wide readership. Section A, however, will be of particular interest to managers and readers interested in KNP per se and who want more detail, as it contains locational information and context-specific detail. Note that there is overlap between Sections A and B (especially in terms of description of methodology). This overlap was allowed in order to ensure that both sections can be read as independent and stand-alone documents. Section C contains a photo gallery to compliment the photos contained in Sections A and B and which aims to act as a visual reminder of the drought effects.

This study collated literally thousands of hours of field observations, often from experienced conservationists, conservation managers, rangers, natural history scholars and scientists, many with particular expertise and interests. This wealth of information is hard to capture in any pre-designed study. However these natural history observations allow for an interdisciplinary, holistic and systemic overview of the drought that compliments formal research studies, some of which are reflected in Section B (see end of section B for an extensive reference list referring to drought studies).

Many ecological lessons, interesting ideas, valuable insights and truly remarkable natural history observations were harnessed from these observations. It is hoped that this largely qualitative, narrated and richly illustrated account of the drought will not only be of interest but also of value for scientists and managers alike during future droughts. The project giving rise to this report aimed to use the drought as a co-learning event between all involved, resulting in a rich and varied report reflecting the different observations and perspectives of the individual respondents experiencing the drought.

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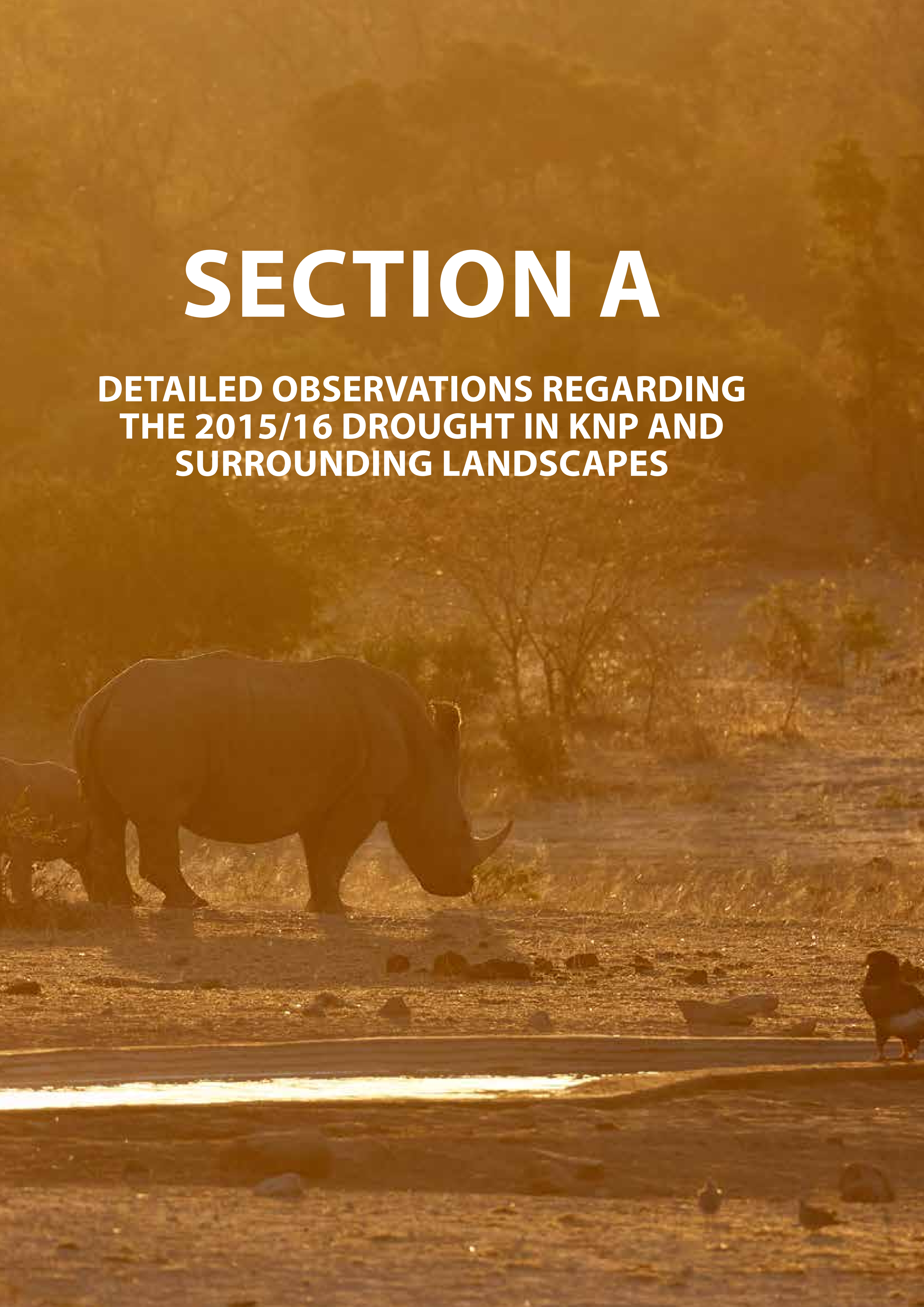
Photo : Rudi van Aarde

Photo: Laurence Kruger

SECTION A

DETAILED OBSERVATIONS REGARDING THE 2015/16 DROUGHT IN KNP AND SURROUNDING LANDSCAPES



1. Background and aim of study

The aim of this quantitative assessment and resulting report is to collect and collate observations and reflections from various colleagues who have lived and/or worked extensively in the Kruger National Park (KNP) and surrounding areas during the 2015/2016 drought. This is in order to compliment various monitoring and research projects which were specifically set up or analysedin such a way as to better understand the effects of the past drought (typically studies that have collected pre and post drought data). Although research projects that specifically focused on the drought are very valuable (some have been published and others are still in the process of being published), many facets of the drought were not studied. Therefore, although rigorous scientific studies are critical for better understanding the effects of droughts, other methods of "learning" from droughts can also increase understanding of these large infrequent disturbances. One such method of "learning" is through general observation from astute observers that lived and/or spend considerable time in the veld (in this case in the Greater KNP) during a drought. It is believed that many ecological lessons, interesting ideas, valuable insights and truly remarkable natural history observations can be harnessed from collecting these largely ad hoc and non-systematic observations. It is believed that some of these observations may also be helpful for scientists in future to formulate and postulate theories regarding the functioning and role of droughts, and/or spark ideas for setting up more specific and rigorous monitoring projects in anticipation of future droughts. Considering the fact that the frequency and intensity of droughts may increase in future, it is important to make optimal use of droughts as learning events in order to increase our understanding of the role of droughts and in order to inform management actions if and where appropriate.

Photo : Rudi van Aarde

2. Methodology of data collection and abstraction of information

Data was collected by requesting colleagues that lived and/or worked in the KNP and surrounding areas to provide feedback on their observations and experiences during the 2015/2016 drought. Colleagues were individually e-mailed (or e-mailed in small groups of closely associated colleagues) and requested to reflect on the drought. The reflection was left very open ended, but four "prompting" questions were used as a way of stimulating feedback:

- What did you see during the drought that was exceptional or unusual?
- Any interesting observations or perspectives on the post-drought period (i.e. what interesting things did you observe after the drought that you think were triggered as a result of the drought?).
- What did you see or perceive during this drought that was similar or different from the previous drought in 1991/1992 (for those that experienced previous droughts in the park)?
- What were the biggest "surprises" for you during this drought and the period thereafter?

Feedback was received from >50 colleagues (more than 70 colleagues were directly requested to provide feedback and some of these colleagues forwarded it to further colleagues). Most respondents provided feedback by means of e-mail, whilst a small proportion provided input through telephonic conversations or sending voice notes. The latter two methods of feedback were captured by the author of this report and were also included in this report. Finally, some information was also extracted from e-mail correspondence regarding observations that was submitted to the Curator of the Skukuza museum during the drought, as well as extracted from ranger diaries.

The report captured and analysed information on three levels of increasing abstraction:

- Level 1 – **Verbatim narratives:** Raw narratives as provided by colleagues (not included in report)
- Level 2- **Cleaned and structured summary of observations:** Raw narratives from level 1 above were cleaned, thematically combined and summarised, but still with a high level of detail (and locational information where provided or deemed important) (Section A: Detailed narratives)
- Level 3 – **Key generalizations:** Key generalizations were extracted from level 2 above. These generalizations focused on identifying consistent and/or pertinent observations. This level of abstraction included some level of interpretation, integration and synthesis from level 2 observations (Section A: Key generalizations derived from narratives; Section B)

A study like the present is unique and valuable in the sense that it collates literarily thousands of hours of field observations, often from very experienced conservationists and natural history scholars, many with particular expertise and interests. Such a wealth of information is hard to capture in any predesigned "scientific" study. Furthermore, this method of data collection allows for an interdisciplinary and holistic view of the drought to compliment more traditional and focused subject-specific studies.

It is acknowledged that the data collection method employed in this study is prone to various challenges, e.g. observer bias or preconceived perceptions of individuals which may subconsciously influence the observations (e.g. observation that lions spend more time around waterholes during drought – is this real, or was this noticed more based on a preconceived perception that this would be expected?). Another challenge is linked to attribution, e.g. can TB that was observed in rhino in KNP for the first time ever during the drought be attributed to the drought or is it coincidental? Also, visibility was improved during the drought, so e.g. certain bird species, or animal carcasses, were more visible which could have influenced perspectives. These challenges should be taken cognisance off as it is inherent in this report. However, it is hoped that key generalizations (Section B) addresses some of these challenges as it is based on multiple observations and is reported on in less detail.

Some of the observations noted in this document are based on scientific studies conducted in the park and have already been published or are in the process of being published (e.g. long-term vegetation study on the Satara Experimental Burn Plots). Some of the other observations or perceptions contained in this report can possibly also be tested by existing data (e.g. the Veld Condition Assessment {VCA} data can possibly be used to test an observation that herbaceous biomass was less resilient on basaltic soils than on granitic soils). Attempts to "test" these observations are beyond the scope of this study, but will hopefully spark interest to explicitly test these in more detail using existing data (or setting up experiments to test these observations/perceptions in future). It is important to acknowledge and be cognisant of the fact that this study contains observations, many of which are accurate, but possibly also perceptions or observations "tainted" by perceptions, and not all observations noted in this report can therefore be considered absolute and objective truths.

3. Key generalizations derived from narratives

This section summarises key messages, with some level of integration and synthesis, which emerged from the more detailed field observations. This is a shortened summary of what is contained in Section B:

- The drought caused **selective mortalities:**
  - Large mammals – mass mortalities were limited to large bulk grazers (buffalo and hippo). Some expressed surprise at the lack of mortalities observed for elephants. The drought was aptly described as a "grazing drought" due to the lack of mortalities observed for browsers (and mixed feeders), and the apparent adequate surface water resources that remained during the entire drought period (see later). Interestingly though, smaller facultative grazers like warthog was not affected like in previous droughts.
  - Woody vegetation: *Dichrostachys cinerea* and *Spirostachys africana* seemingly experienced wide and relatively large-scale die-offs, whilst other species like *Terminalia sericea, Acacia welwitchii, Commiphora mollis, Peltophorum africanum, Euclea divinorum* and *Trichilia emetica* died off in certain areas or patches. Although not widely reported, some large individuals of *Acacia nigrescens* and occasionally *Colophospermum mopane* and *Combretum imberbe* also died off in specific localities. An interesting observation was that some trees died slowly after the drought (i.e. only clearly observable a couple of years after drought), which suggests a different mortality process as compared to animals.
- **The temporal distribution of rainfall**, and not just the absolute amount of rainfall, may have had a disproportionally large effect in terms of how mammal mortalities played out. It was suggested by some that key rainfall events buffered large mammal mortalities. It is hypothesised that specific rainfall events, especially the relatively large and wide-scale rainfall event in March 2016, may have been instrumental in reducing large mammal mortalities – it may be worthwhile to explore how rainfall distribution differed between the 2015/16 and 1991/92 droughts and whether this may be responsible for some of the differences in mortality rates (and species affected; see later).
- **Lack of food as opposed to lack of surface water** was clearly and consistently noted as the reason for large mammal mortalities by many of the respondents participating in this study. The **role that groundwater played in sustaining springs and pools in rivers** was very noticeable and reported widely. Groundwater was a slow responder to droughts (as opposed to surface water that dried out quickly) and played a key role for various aspects of biodiversity (pools and springs providing water for animals and acting as refugia for aquatic biodiversity, and probably also sustaining larger trees in riparian areas with access to groundwater resources).
- Various **"outbreaks" occurred during the drought, but especially in the first wet season after the drought** – these outbreaks were observed across various taxonomic groups:
  - *Rodents:* Wide-scale explosion of rodents in southern and central KNP – this was very obvious and noticeable with Sherman trapping success (~40% trapping success pre-drought; ~5% trapping success during drought and ~80% trapping success first two winters post drought, only back to more normal levels of 10-30% in third winter post drought). It was also noticeable for many respondents with rodents continually crossing roads at night, tourism complaints about rodent infested accommodation and damage to infrastructure. This outbreak of rodents co-occurred with increasing observations of spotted eagle owls (Skukuza/Pretoriuskop granites) and grass owls (Lower Sabie basalts).
  - *Fish:* Explosion of southern barred minnow (*Opsaridium peringueyi*) in Sabie river and three spotted barb (*Barbus trimaculatus*) in Letaba river during the drought.
  - *Insects:* The explosion of the moth, Banded Achaea (*Achaea catella*), during the drought and others like a small, black stink bug (*Strombosoma impacta*) in the first summer after the drought.
  - *Birds:* Massive red billed queleas outbreak in the year after the drought – the outbreak was larger than any previous one in living memory.
  - *Forbs:* Forbs and geophytes dominated the herbaceous layer during drought whenever a small rainfall event occurred and also in the first year after the drought – in normal years grass biomass would dominate. In some places large areas would be covered by certain forb species (e.g. *Albuca seineri*, *Ammocharis coranica, Indigastrum parviflorum*, *Sida sp*, *Hibiscus sp*, *Melhania sp*, etc. to name but a few). Forb responses seemed to be very site specific, and could vary between diverse forbs, to patches dominated by one species (although forb diversity seemed similar to normal years, the cover/biomass was much increased).

- Linked to the point above, various cases were reported of an **outbreak or large boom** after the drought which was speculated to be **linked to "release" factors or reduced competition**:
  - Malaria cases increased in 2017 – this may have been due to adequate water in the post drought year for mosquito breeding, but "release" from mosquito predators which needed more time to recover in order to "control" mosquitoes again.
  - Outside KNP, it was noted that seeds and seedlings (especially for *Acacia* and *Aloe* species) were more prevalent after drought possibly due to low density of seed predators post drought (among other factors).
  - Forbs made use of the drought "disturbance" effect and dominated bare areas after rainfall events during drought as well as in the first rainfall season post drought, before grass dominated again (possibly forb "release" from competition with grass).
- Various **large-scale movements of mobile species** were observed and various species were recorded outside their normal distributional ranges:
  - *Birds:* Some bird species were recorded in KNP that do not normally occur here or are rare (e.g. Marico flycatcher, red-capped lark, Narina trogon, pelicans, European wheatear), as well as some common species that were less common during the drought.
  - *Freshwater jellyfish:* Although hard to attribute to drought, it was interesting to note that the first ever record of freshwater jellyfish (*Limnocnidae tanganjicae*) recorded in KNP was during October 2016 at the height of the drought (at Red Rocks in Shingwedzi river). The second ever record was noted two years later in November 2018, again at the end of a dry and warm winter and in rock pools of an ephemeral seasonal stream (Bangu spruit, tributary of Olifants river >100 km south-east from first location). This jellyfish species is better known from further north in Africa where it occurs in large lakes as opposed to small rock pools/potholes.
- Various mobile species moved to areas or increasingly utilised areas where conditions were more favourable**,** supporting the notion that certain areas can act as **drought refugia**:
  - Buffalo and elephant densities seemed to have increased around rivers during drought.
  - When water sources dried up or grazing conditions deteriorated around regular locations, hippos moved into springs and seasonal pans where they normally don't occur or occur in low densities.
  - Skukuza staff village was heavily utilised by browsers (and hippo) during the critical period of the drought. On days of extreme heat, insects swarmed uncharacteristically in shaded undergrowth in gardens.
- Various lesser studied taxonomic groups (and in some cases specific species within these taxonomic groups) may have been severely influenced by the drought. **The reduction – described by some as a total "collapse" - in invertebrate numbers** was very apparent, widely observed and noted by numerous respondents. This reduction in abundance and biomass was noted for insects in general, some specific insect groups (e.g. dung beetles, moths, stick insects) but also for other invertebrate groups (e.g. orb spiders and millipedes). **This reduction in invertebrate biomass could possibly have cascading effects on various other taxonomic groups**. For example, reptile abundance (i.e. snakes, tortoises and chameleons) were also noted to have decreased, and emaciated and tame/disorientated civets (with millipedes as important food resource) were observed. During the next drought the population crashes in invertebrates (and taxonomic groups feeding on them), and their subsequent recovery, need to be more closely monitored. The predominant focus on the more charismatic groups (like large mammals and to a lesser extent vegetation) may result in crashes of entire food webs going largely unnoticed.
- The **most apparent difference between the 1991/1992 and 2015/2016 drought was the surprising lack of mortalities of species that were noted to be the most sensitive during previous droughts** (impala, bushbuck, warthog and kudu). In addition, there were in **general lower mortalities observed during the recent drought** when compared to the 1991/1992 drought (the only species that seemingly suffered bigger mortalities in recent drought was hippo). The **patchiness of the recent drought**, the **occurrence of rainfall at critical periods** and the **closure of artificial waterholes** were the most common reasons presented for this surprising lack of large scale mortalities other than hippo (and buffalo).
- **Forage resources that are not normally utilised by herbivores, were utilised during the drought.** This included various grazer species actively browsing or eating leaves (observations of buffalo and sable actively browsing and blue wildebeest eating leaves), as well as herbivores feeding on species usually considered unpalatable (e.g. buffalo grazing *Pennisetum sphacelatum;* elephant and buffalo browsing *Phragmites* reeds; giraffe browsing on *Philenoptera violacea* and buffalo wading deep into water to browse on water lilies *Nymphaea sp.*). Many forbs were also observed to be browsed, although it is not clear whether forbs were browsed more than in normal rainfall years. It is not

apparent how much energy herbivores can extract from these "poor quality" resources, but these may possibly be critical resources during severe droughts. The nutritional importance and value of these resources can be explored in future droughts, to determine whether these resources act as critical "bridging" resources or are only eaten in an attempt to alleviate the hunger (or possibly to keep their rumen or stomach micro-flora active).

- **Behavioural changes** were observed for various species, e.g. lions spending extended periods around waterholes, predators sharing food without displaying the normal rivalry (e.g. spotted hyena and leopard as well as spotted hyena and black-backed jackal feeding simultaneously on the same carcass); large buffalo herds fragmenting into small groups, elephants moving into specific areas, some species becoming very tame (e.g. bushbuck and especially nyala in Skukuza staff village; civet) whilst others showed more aggressive behaviour (buffalo cows towards humans on foot), earlier emergence time for various species in order to increase available feeding periods (e.g. hippo, bats, birds).
- Drought seemingly **impacted on calving/lambing** of some species, with buffaloes having almost no calves in central KNP during year of drought or first year post-drought (i.e. due to lack of conception during drought), and impala having seemingly less, and more asynchronous, lambing than usual.
- Various seemingly **rare or atypical disease occurrences** occurred during the drought period, including the first ever diagnoses of tuberculosis (TB) in white and black rhino in KNP, as well as first ever human TB observed in a wild elephant. Also, for the first time in many years, African wild dogs were diagnosed with distemper (and an entire pack died as a result). Reports of mange were more common in predators than usual. A few elephant mortalities were noted after the drought where encephalomyocarditis was expected (although not positively diagnosed), especially considering that the host of this virus is rodents which experienced a massive outbreak after the drought (see earlier). Mass mortalities of laughing doves, possibly of pigeon paramyxovirus (diagnosed as such elsewhere in Mpumulanga) occurred widely in central and southern KNP. Interestingly no large-scale anthrax outbreaks were experienced during the past drought like during the 1991/92 drought (one can speculate whether it may be linked to closure of artificial waterholes in the north of KNP that previously assisted vultures in spreading this disease quickly over large distances). It is however very difficult to make direct links between the disease occurrence described above and drought, although malnutrition always has linkages to impaired immunity, and thus potential disease/disease-related mortality. Furthermore, the concentration of animals around scarce water and food resources increases intra/interspecies contact rates, which could also play an important role in the extent of disease spread compared to normal conditions.
- **Rivers were actively managed** during the 2015/16 drought and based on measured and archived flow data, most rivers recorded better flows during the 2015/2016 drought as opposed to the 1991/1992 drought. **Management intervention was at a catchment scale** and focused on dam releases negotiated at high political level from upstream dams and through imposing water restrictions across various sectors. The irrigation restrictions had implications on the farming sector (and job security) outside of KNP.
- **Herbaceous biomass was severely reduced during the drought, with many perennial grass tussocks dying** – this mortality of perennial grasses was seemingly more common in areas with herbivore presence. Once the rains returned, **forbs and annuals were the first herbaceous functional groups to return** to the bare areas, resulting in a changed herbaceous species composition remaining in the grass sward. In some cases the grass layer that returned after the drought was more palatable than the grass layer before the drought.
- Both the commercial and the subsistence **farming communities bordering KNP were severely affected and suffered financial losses** due to cattle deaths and irrigation restrictions.
- **Drought interacted with the underlying template (geology) and disturbance regimes (i.e. fire history and herbivory):**
  - Herbaceous biomass loss seemed more pronounced and post-drought recovery more exuberant on basalts compared to granites. Also, termite activity seemed more pronounced on basalts than granites.
  - Disturbance and disturbance history (grazing and fire) interacted with drought – perennial grass survival seemed reduced in areas where grazing occurred as opposed to areas where grazing was excluded. Similarly, herbaceous biomass standing crop reduced more on burnt than unburnt areas.
- Lessons from previous 1991/92 drought resulted in management actions that improved the situation during the 2015/16 drought:
  - Previous drought "forced" **opportunities for cooperation with neighbours and relevant state departments**, inter alia as river forums, some of which were still operation during the 2015/16 drought.
  - The rivers sustained flows better during 2015/16 drought than 1991/92 drought. The improved situation shows that the strategic decisions taken at that time to provide for **rivers from dams (at that stage still to be built) in the upper catchments** have worked.

- **The density of artificial waterholes in KNP was reduced** by closing a number of waterholes since the 1991/92 drought. There were various reasons for closing the waterholes, inter alia due to the negative effects of them during drought periods. Although hard to "prove" the effectiveness of this management approach, many respondents explicitly commented on the lack of food rather than the lack of water as driver of herbivore mortality and some also ascribed the lower mortality rates during 2015/16 drought compared to 1991/92 drought to the increased availability of reserve/buffer forage in water remote areas. Movement between KNP (possibly for forage) and the private protected areas to the west of KNP (possibly for water) was observed for species like buffalo.
- Although there were similarities with previous droughts (1981/82 and 1991/92), there were also major differences (e.g. in terms of large mammal mortalities; red billed quelea eruptions). **No two droughts are the same** and predictability remains low, with surprises to be expected.


Photo: Laurence Kruger

4. Detailed narratives/observations

This section is a collation of the narratives provided by colleagues regarding their observations and perceptions regarding the 2015/2016 drought under relevant section headings and subheadings. The final subsection (4.12) compares the 2015/2016 drought with the drought of 1991/1992 based on recollections from colleagues that have experienced both or had oral recollections from former colleagues that experienced the earlier droughts.

4.1. Climate/Rainfall

- The 2015/2016 drought was expected well in advance (based on El Niño predictions) and awaited in anticipation as an opportunity to learn rather than an event that must be dreaded.
- Although the total amount of rainfall was very low and qualified as a severe drought in central and southern KNP (Figure 1), there were months (like March 2016) that recorded good rain (Figure 2), which sustained surface water in some river pools and small pans. For example, March 2016 received just over the long-term average rainfall (106%) when considered across all KNP rainfall stations, with two rainfall stations (Pretoriuskop and Mooiplaas) reporting over 250mm for the month (more than other rainfall stations in the central and southern KNP recorded over the entire rainfall season).

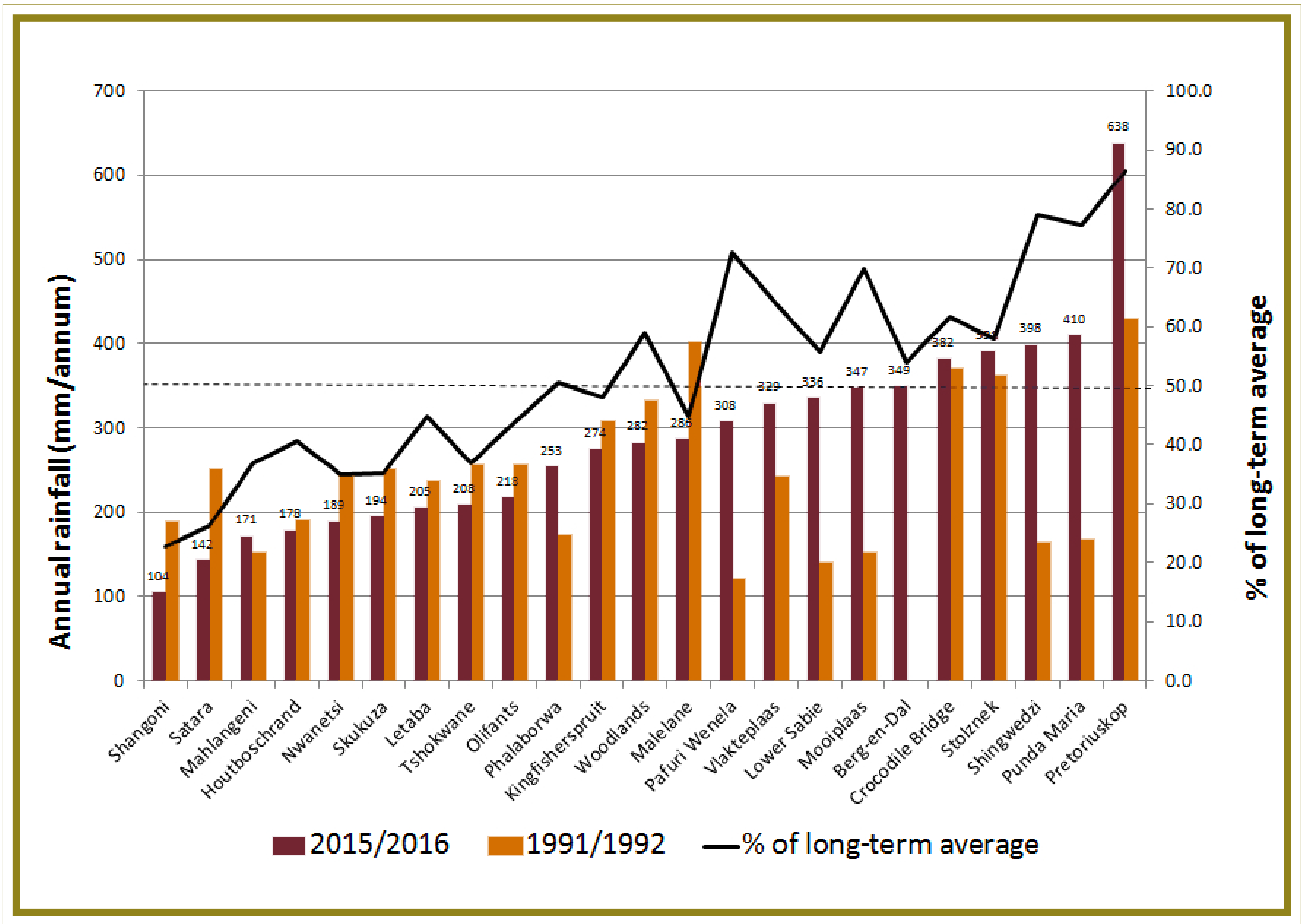


Figure 1: Comparison of 2015/16 and 1991/92 rainfall recorded at the KNP rainfall stations (rainfall data for Shangoni may be incomplete).

- Rainfall at critical periods may have played a significant role in reducing mortalities for species like warthog and kudu. For example, in Houtboshrand every 2 months some critical rainfall was measured (November 2015, 22.4mm; January 2016, 40.9mm; March 2016, 81mm) which may have sustained the surface water sources and food for the non-bulk feeders, but not for the bulk grazers like hippo and buffalo.
- Dust storms and dust devils were common throughout the drought period, sometimes turning the sky murky/ dark. One colleague commented that the increased dust in the air increased sky-glow from light pollution and also contributed to even more dramatic sunsets than normal (Figure 3).

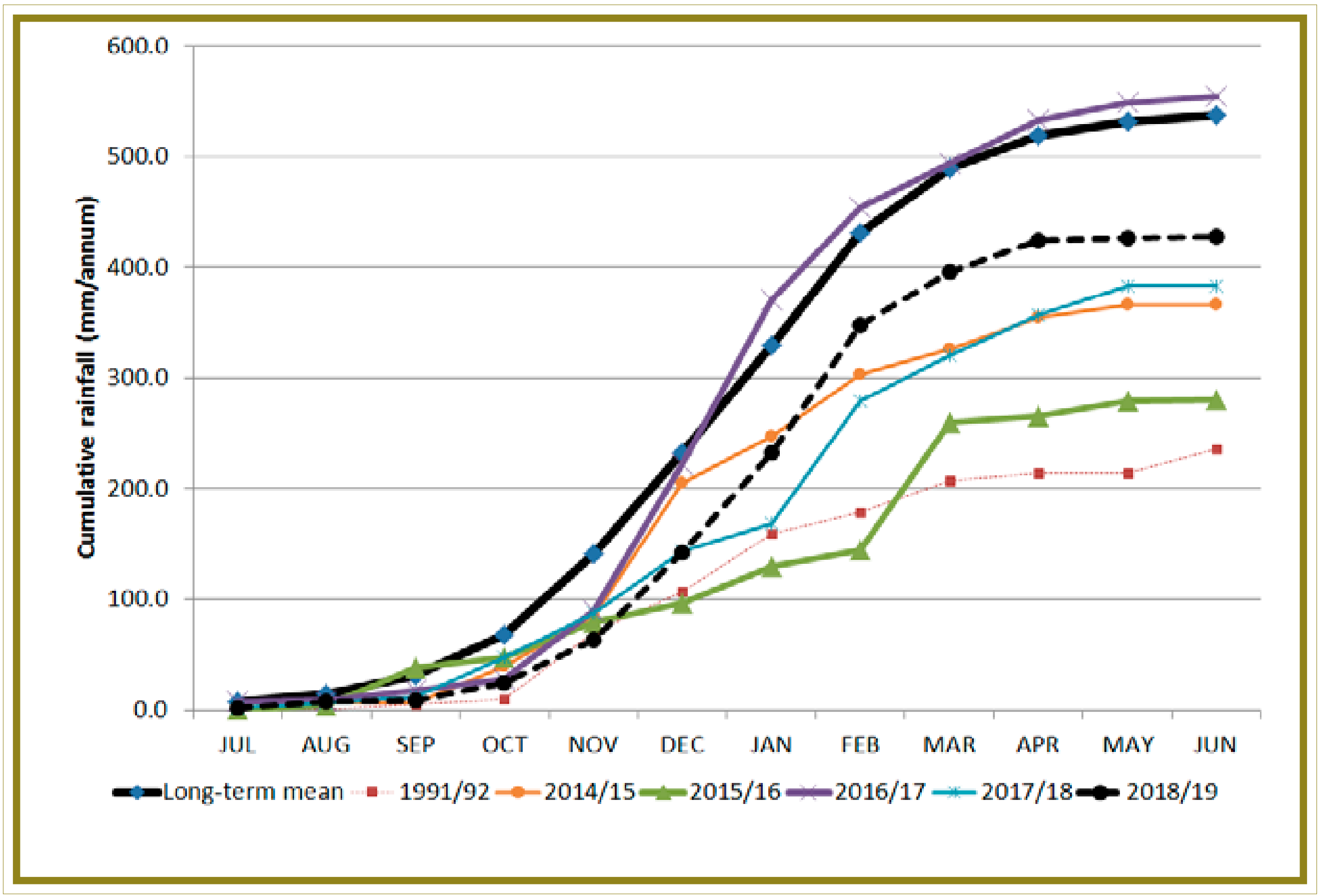


Figure 2: Cumulative average rainfall across weather stations spread throughout the KNP. KNP has been in a dry-cycle since 2014/15 up to and including 2018/19, with four of the past five years experiencing below or far below average rainfall conditions. Note, also, the comparison of cumulative rainfall between the 1991/92 and 2015/16 drought, with the uncharacteristically good rainfall recorded during March 2016 a distinguishing difference between these two droughts.

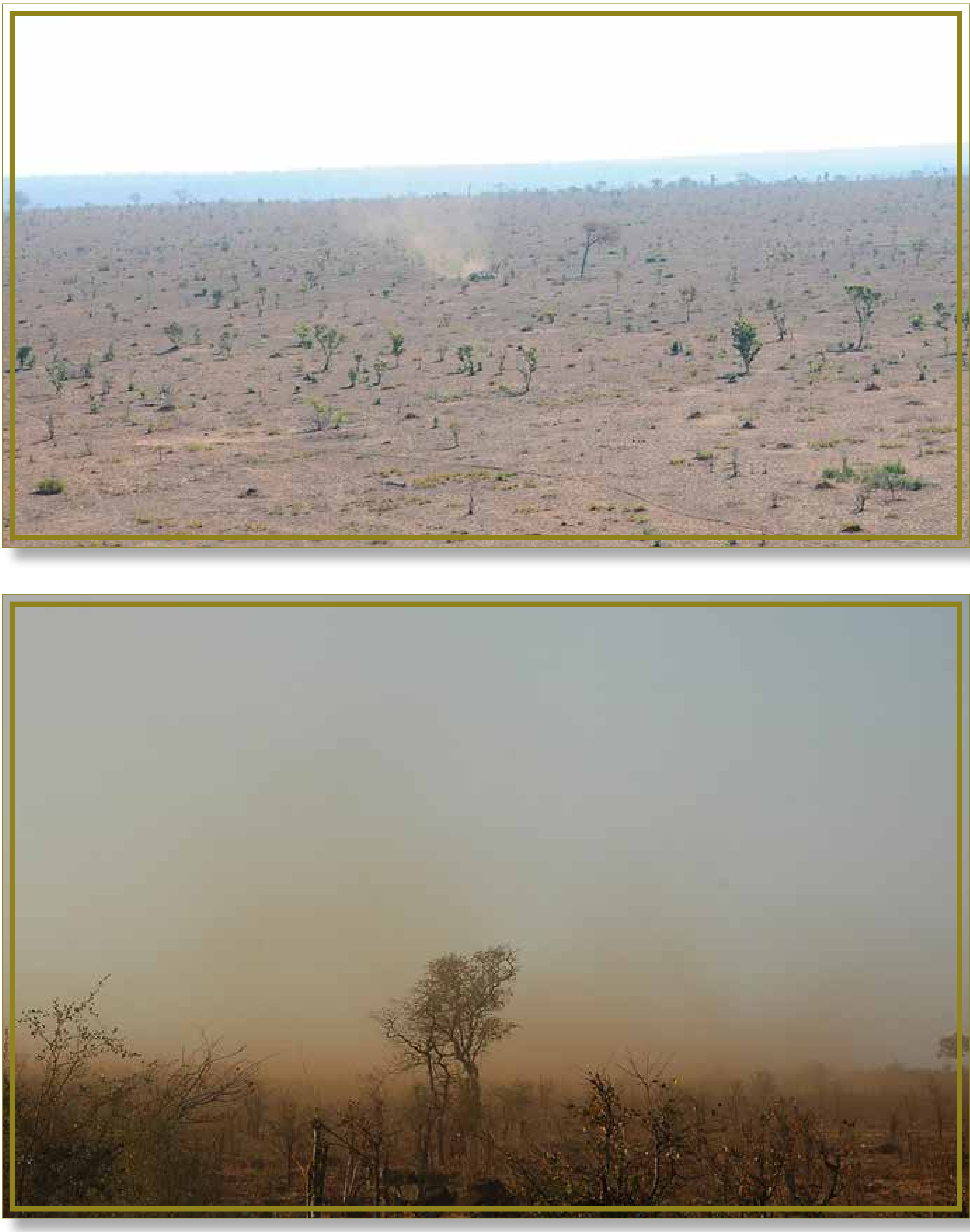
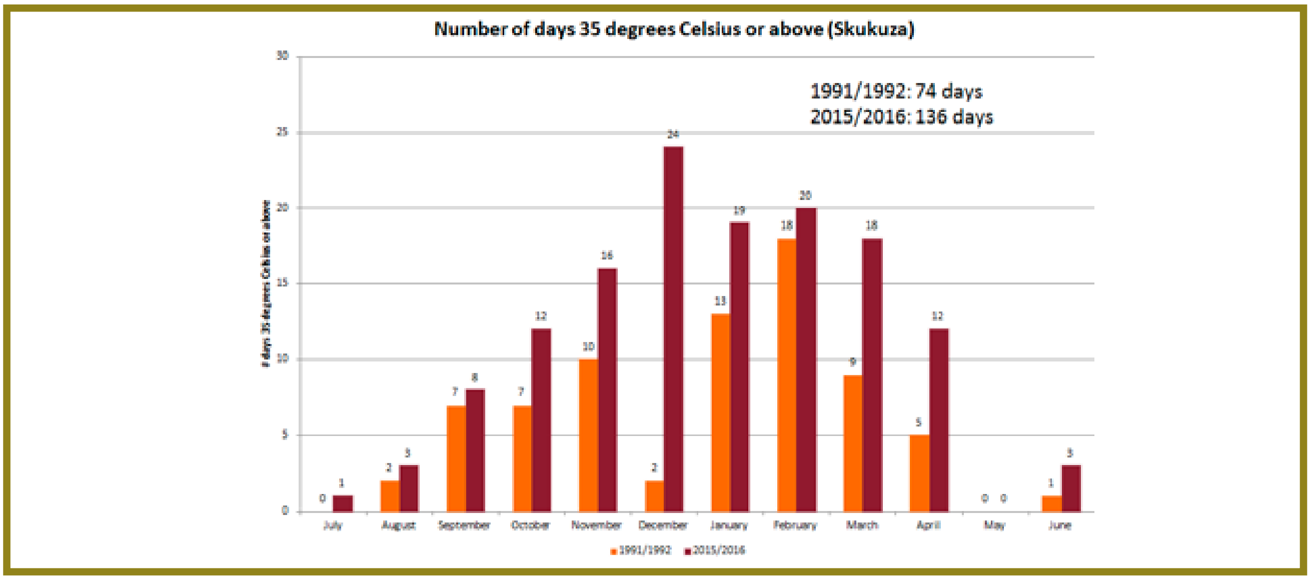


Figure 3: Dust devils (top) (photo: Cathy Greaver) and dust storms (bottom) (photo: Izak Smit) were common during the drought.

- Extreme high temperatures were experienced – this has been confirmed for Skukuza weather station which recorded the warmest summer on record (daily temperature records available since 1960 for Skukuza). There were more days over 40 degrees centigrade measured than in any prior year (Figures 4-5).



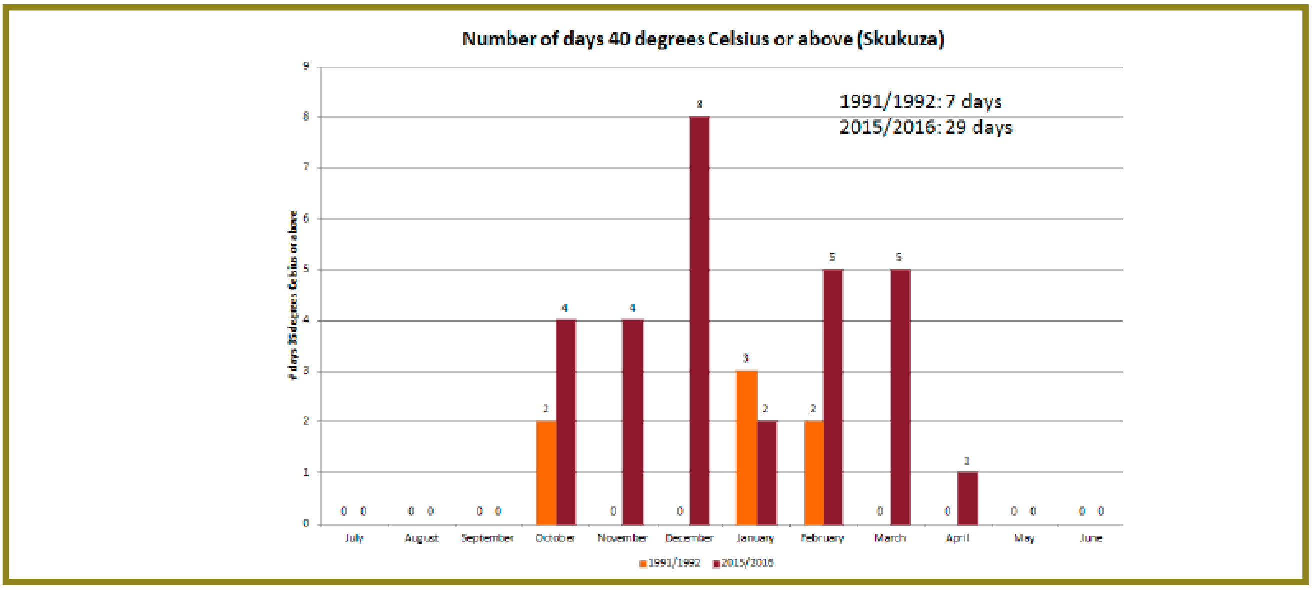


Figure 4: Days of **e**xtreme temperatures at the Skukuza automatic weather station were more common during 2015/16 drought as compared to 1991/92 drought (data kindly provided by SA Weather Services; analysed by Izak Smit).

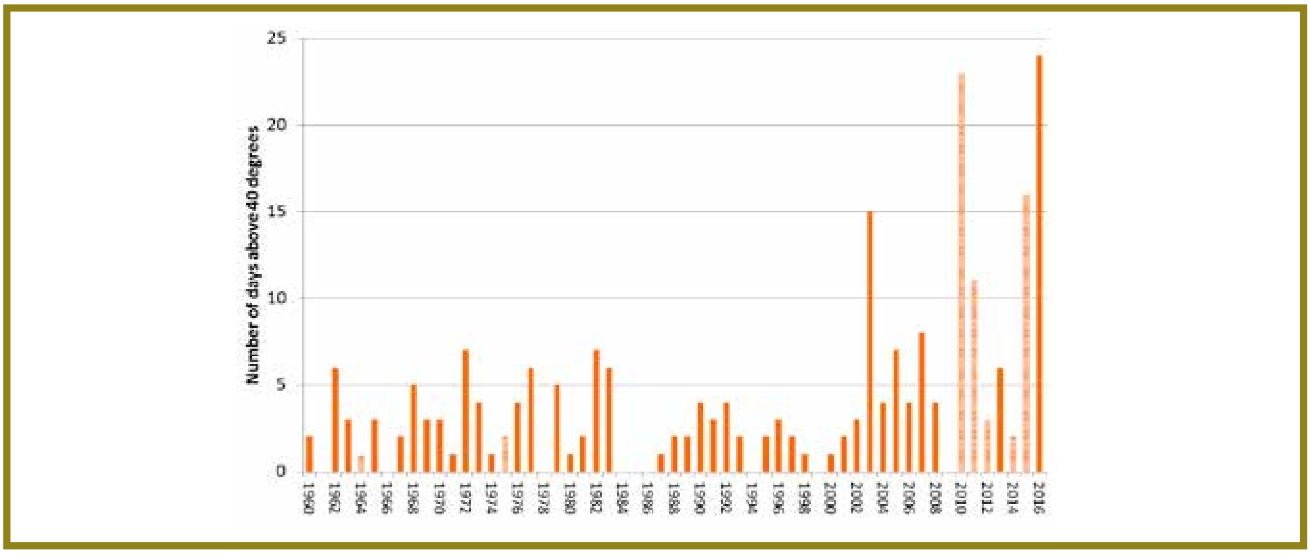


Figure 5: Number of days above 40 degrees centigrade measured at Skukuza Weather Station (years with non-solid bars have data missing; data kindly provided by South African Weather Service and analysed by Izak Smit).

Figure 6: The 2015/16 drought was a "grazer" and not a "browser" drought, and woody vegetation continued to be in leaf after most herbaceous biomass has vanished during the summer season (top photo from Nkumbe lookout; Izak Smit). However, during the ensuing winter, browse on deciduous trees also declined considerably and browse availability also became limited (bottom; photo: Cathy Greaver).

4.2. Large Mammal Mortality

- Hippo and buffalo were the only species noted to die on large scale. This mortality was centred in the central KNP and adjacent private protected areas.
- The lack of other large mammal species dying, especially impala, bushbuck, kudu and warthog, was surprising compared to previous droughts (see 4.12). Timbavati Private Nature Reserve recorded one waterbuck, one nyala and one kudu dying, as well as some (but relatively small scale) impala mortality as a direct result of the drought (however, scavengers remove these smaller carcasses so fast, so some under-reporting can be expected). Also, these isolated mortalities are likely more indicative of pre-existing conditions being expressed rather than drought induced (i.e. starvation) mortality *per se*.
- The 2015/2016 drought was considered a "grazer" drought (Figure 6), and it was most severe in the central district of the KNP (Tshokwane, Satara, Nwanetsi and Houtboschrand sections), with effects seemingly more pronounced on the basaltic areas compared to the granitic areas. Bulk grazers (i.e. hippo and buffalo) started dying already early during the summer (January 2016) in Tshokwane section. In March 2016 good rain was recorded (Figures 2 & 7) which seemed to have provided a reprieve in Tshokwane section and the mortalities "ceased" for a while, starting again only later in the season – without the March rainfall event, the mortalities would probably have been much higher. In Nwanetsi section the mortality seemed to increase from February 2016 onwards, and continuing for hippo even after the March 2016 rainfall (which was rather limited in Nwanetsi).

Figure 7: Good late rains (March 2016) were followed by some grass growth (especially in areas where there were still some grass "stubble" around) (top) and forb emergence (especially in bare patches) (bottom) – it is believed that this may have played a critical role in reducing the mortality rate of the non-bulk grazers, and it even seemingly resulted in a reprieve of mortality of hippo and buffalo in certain parts of the park (photos: Izak Smit).

Figure 8: Emaciated hippo fell prey to lions (top) (Nwaswitsontso river; photo: Izak Smit) or died due to starvation and exposure even in areas far from water in search of food (bottom) (photo: Danie Pienaar).

4.3. Responses of various taxonomic groups

4.3.1. Large Mammals

4.3.1.1. Hippo

- Emaciated hippos were common and many hippo carcasses were found within and next to rivers, but also in areas far removed from water where they were feeding and got too weak to return to the water (Figure 8).
- Unusually large concentrations of hippos were observed crammed into small remaining water bodies (Figure 9). As large earthen dams dried up all those hippo moved to fewer and permanent pools in seasonal rivers and springs.
- Hippos were observed far from the remaining water sources in search of forage (Figure 10).
- Hippo bulls were sometimes found far from hippo herds with some of them having visible signs of injuries from fights.
- Cases of hippo being predated by lion were observed in Tshokwane and Nwanesti sections (Figure 8).
- Pre-drought survey in Nwanetsi section in small streams (Guweni, Mavumbye and Mapetane) counted ~375 hippo (excluding any dams) – after drought only 15 were left at Sweni hide and Guweni spring (drop attributed mostly to natural mortality, although some were culled; movement to other areas expected to be minimal).

Figure 9: Hippos aggregating in large groups in small remaining water bodies – this also reduced the quality of water in these remaining water bodies due to turbulence and defecation (top photo: Cathy Greaver; bottom: Robert Bryden)

Figure 10: Hippos were sometimes found far from water in search of food and extended their forage time extensively into the day time (photo taken close to Jones' dam early in the afternoon; Izak Smit).

Figure 11: Hippo cow and calf in last bit of remaining water/mud (Nwanetsi section; photo: Robert Bryden)

4.3.1.2. Buffalo

- Buffalo herds fragmented into smaller groups, even as small as five, which probably assisted them in finding adequate food and reduced feeding competition from other herd members. It took considerable time after the drought (deep into the wet season of 2017) for buffalo herds to get back together into the large pre-drought herds (Tshokwane & Kingfisherspruit sections). In the northern regions of the park (e.g. Mooiplaas) where the drought was less severe, the buffalo herds were not observed to break up into these smaller splinter groups as was noticed further south.
- In the Timbavati Private Nature Reserve (TPNR) the herd sizes also dropped from 250-340 animals per herd to 3-7 animals per herd, with the herds widely distributed across the property. The buffalo population was higher in areas within TPNR with higher rainfall (south) than the drier parts (northern and central TPNR). The mortalities in TPNR were observed between September and October 2016 (about 49 carcasses recorded, with probably a 20-30% undercount bias). It is believed that the large reduction in buffalo in the reserve (from about 3000 to 1000 between 2015 to 2017) was mostly due to movement out of the reserve, as the park is heavily patrolled on foot and the number of carcasses found could not account for the large drop in densities.
- In the Tshokwane ranger section the mortalities started rather abruptly in January 2016, which was also the month in which most carcasses were recorded (Figures. 12). After March 2016 it tapered off, possibly due to good rainfall during that same month. Buffalo mortality started again in November 2016 until rains returned in December 2016 (Figure 13).

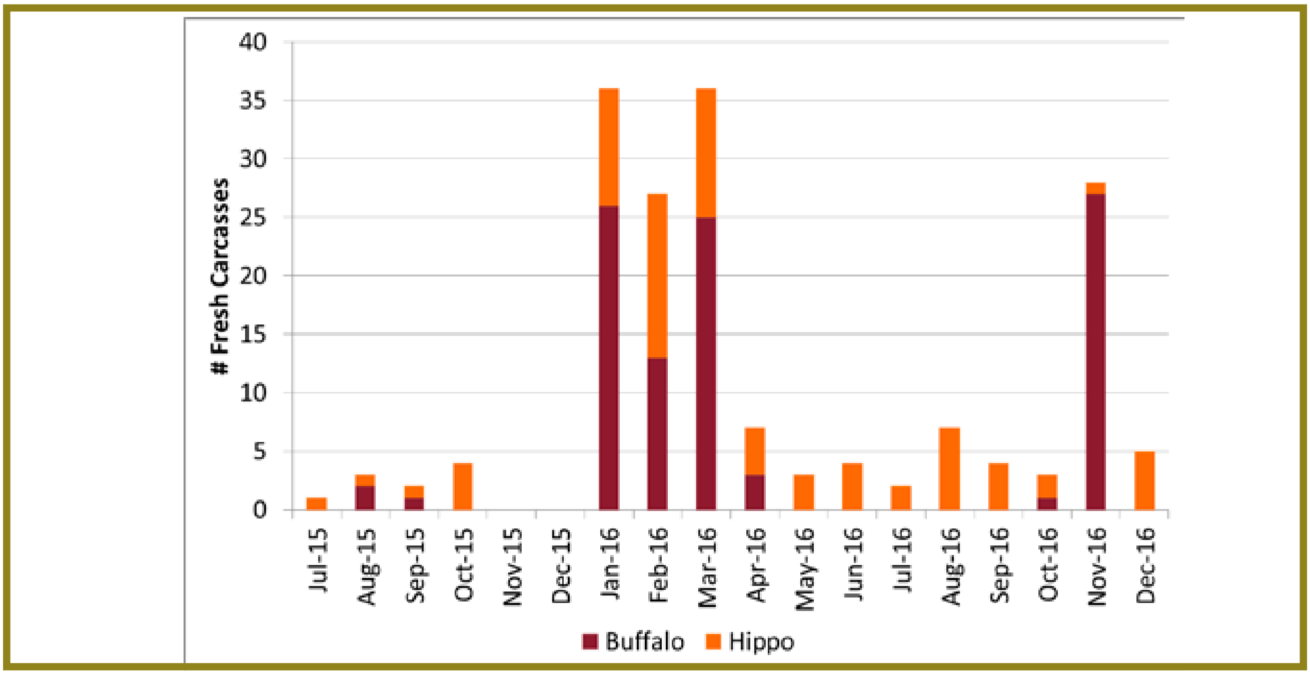


Figure 13: Fresh starvation-induced hippo and buffalo carcasses recorded in Tshokwane and Nwanetsi ranger diaries (not including predated on individuals) – note the spike, especially for buffalo, between January 2016 to March 2016. Hippo mortalities also peaked in January – March 2016, but continued throughout the dry season (data extracted from Tshokwane and Nwanetsi Ranger diaries).

- The buffalo mortalities were mostly calves under 5 years and animals over 12 years old.
- Buffalo died in small "clusters" (~5-6 animals sometimes), sometimes reported by field rangers as disease, but most likely malnutrition. It is expected that this may have been where the herd rested over night and these individuals were too weak to get up when the herd moved on in the morning – Tshokwane section ranger indicated that he has not seen this clustering of mortality before even during previous droughts. Buffalo was totally absent from Nwanetsi section for over a year during the drought period.
- The drought affected the breeding of buffalo in the southern and especially central KNP. In 2016 (drought year) there were few small calves and only a small proportion of pregnant cows (based on State Veterinarian abattoir inspections). In 2017 (one year after drought), there were virtually no calves and almost no cows lactating or pregnant (based on State Veterinarian abattoir inspections). In 2018 there was an increase in pregnancy of cows, but it was noticeable that there was a missing cohort of calves between the ages of 6-18 months. Buffalo in the Satara buffalo camp which received supplementary feeding during the drought had some calves, although also very limited.

Figure 12: Buffalo and hippo had the largest mortality rates of the larger herbivores, with very little mortality observed for other mammalian herbivores during the 2015/16 drought (top photo: Izak Smit; bottom photo: Guin Zambatis)

Figure 13: White rhino in very poor condition, Nwanetsi section (photo: Robert Bryden).White rhino, especially in the central district, were affected during the past drought whereas no impact on white rhino was noted or noticed during the 1991/92 drought.

4.3.1.3. Rhino

- The condition of rhinos was not detectably bad in the Malelane section, and they seemed to stay in their territories. White rhino in the central district lost condition due to the drought and were visibly thin (Tshokwane and Nwanetsi) (Figure 13). Some mortalities of (old) adult animals directly attributed to starvation were observed (at least three in Nwanetsi section) with mortalities of calves probably going undetected (Figure 14).

Figure 14: Rhino dead from starvation in Nwanetsi section (photo: Robert Bryden).

- White rhino did not conceive and calf during drought, but almost all cows that could, have subsequently calved when conditions improved again (Nwanetsi section).
- In Kingfisherspruit one white rhino carcass was found to presumably have died of drought. In Tshokwane and Nwanetsi white rhino in poor condition was observed and a couple of carcasses attributed to starvation (at least three mortalities, of old individuals, attributed to starvation in Nwanetsi section). In Timbavati Private Nature Reserve five white rhinos died during the drought – two were directly drought-related (weak animals that could not move and had to be euthanized), and three due to natural injuries (two were bulls, expected to be due to territorial fights, which seemed to have increased during drought period).
- Increased sightings of black rhino observed in Malelane section.
- White rhinos appeared more clustered during the aerial survey conducted during the drought (2016) (Figure 15).
- Rhino in the Tshokwane section moved from the denuded plains into the Lebombo mountains where some grass was still available during the drought. It was also observed that white rhinos walked increasing distances between forage and water resources.

Figure 15: Rhinos seemed to cluster during the drought (photo: Cathy Greaver).

4.3.1.4. Elephants

- Elephant mortality was expected by some respondents, and it was anticipated that the drought may play a role in regulating/decreasing elephant population as was noted in Tsavo NP (Kenya) and Hwange (Zimbabwe) during previous droughts. The fact that this did not happen at a significant scale suggests that a more severe or protracted drought would be needed to impact elephant survival. This was a valuable lesson to be learned and may need to be considered for elephant management in future.
- In the Nwanetsi section which was severely affected by the drought some older adult bulls and cows died as a direct result of the drought, as well as some calves. The calf mortalities may have been due to the mothers dying or more likely their milk drying up due to malnutrition. Two cases of elephant calves being killed by elephant were reported in Nwanetsi section. One case of an adult cow in Timbavati Private Reserve was also observed. Various elephant in poor condition were observed e.g. in Tshokwane section. However, these were specific individuals and not common at the scale of the entire population. In 2019, about 21-22 months after

drought (i.e. gestation period of elephants), massive calving has been observed with every cow that can having calves (cows likely did not get into oestrus during drought, but shortly thereafter when conditions improved).

- No big behaviour changes observed for elephants except bigger numbers in and around river systems, and with their diet focusing more on roots of woody plants and reeds in rivers. Elephants were also seen moving into the Mooiplaas section in large numbers, possibly linked to more favourable conditions around the Tsendse river (note that Mooiplaas recorded 255 mm rain in March 2016 which may be responsible for some of this movement).

Figure 16: Various skinny elephants were observed (top photo close to Letaba; Cathy Greaver; bottom photo close to Tshokwane; Izak Smit) , but in general their condition was not noticeably affected. Only isolated cases of mortality directly related to the drought were observed.

4.3.1.5. Other large mammals

- Higher mortalities were expected in browsers than what was observed - with the rain in small quantities but well spread over time it looked like there was some growth available on the shrubs and trees for long periods, which probably sustained these species through the drought.
- A perception was expressed that waterbuck numbers may have dropped and it was suggested that high predator densities around water during the drought may have contributed to this (see 4.3.1.7.).
- During aerial surveys more sable herds were observed than during previous surveys, especially in areas close to the Sabie river. Not sure whether this may have been due to increased visibility.
- During the end of 2016, impala births were significantly reduced and were a lot more haphazard than the usual synchronous birth period. There seemed to still be a lot of "odd" sized lambs around some time after the drought, so possibly a bit of a disruption in synchrony in those ewes that did not take/had abortions/foetal resorption.
- In the Mooiplaas section of the park, where rainfall was not as low as in areas further south, species like tsessebe and blue wildebeest, but also roan antelope and zebra were seemingly calving better than usual during the drought period. With Mooiplaas receiving over 250 mm in March 2016, it may have acted as some "refugia" during the drought.
- Blue wildebeest and zebra numbers have been increasing since 2015 in the Timbavati Private Nature Reserve – they may possibly have been advantaged by the drier conditions. Buffalo numbers plummeted on this reserve (about two thirds reduction) between 2015 and 2017, and started recovering in 2018 (most of this is ascribed to movement out of reserve rather than mortality within the reserve).
- A trails ranger reported signs of aardvark and aardwolf in more than one area in the park on trails, and also noted plenty of signs of pangolins.It is not apparent whether this is due to increased activity of these animals, or possibly easier detection of their signs.

Figure 17: Numerous cattle died off in areas adjacent to KNP, especially in the northern Giyani areas (photo: Tony Swemmer).

4.3.1.6. Cattle in communal rangelands outside KNP

- Cattle deaths were far more common in Mopaneveld areas of Giyani, than the villages of Bushbuckridge further south (Figure 17). Not clear whether this was due to rainfall deficits being more severe there, or because the grass layer was more degraded and less productive prior to the drought. Drying out of small dams (not pumped waterholes) seemed to be the trigger as cattle could not reach the "reserve" forage areas in these water remote areas. This lead to cattle being watered using water tanks erected close to a village, or at the only remaining dam in the village. All forage around that water point was soon exhausted, and cattle were surviving on feed purchased by owners. When the owners could no longer afford feed, then cattle died. More reliable waterholes in grazing areas may have reduced cattle mortality, but would have had a negative impact on the grass layer over a wider area.
- Cattle deaths did still occur in higher rainfall areas (i.e. areas further south), and cattle certainly looked skinny in these areas, but it seems that drought-associated deaths in these areas may have been a result of disease and plant poisoning combined with inadequate forage, rather than a complete lack of forage (as was observed further north). For example, an Environmental Monitor at Craigieburn village (which is west of Acornhoek, about 700mm MAP in normal years) reported that a cow had died after eating a poisonous plant (possibly 'gifbol').
- Neighbouring Zimbabwe also experiencing severe drought conditions (in 2018/2019 drought in Pafuri region of KNP), with cattle crossing to graze the little vegetation left in KNP – the drought in Zimbabwe seemingly also increased the intensity of snaring for bush meat within KNP.

4.3.1.7. Predators

- Lions spent considerable time around the remaining water sources and around rivers – the Tshokwane section ranger observed lions killing five buffalo around a single waterhole (Figure 18). Lions would simply stay at remaining water sources and wait until the accumulating herds grew desperate enough to attempt to drink despite their presence. So not only was there minimal forage left around remaining water sources, but survival was further compromised due to predation at these water sources.

Figure 18: Increased predation rates were observed on buffalo – when this photo was taken, three carcasses were found within a 500 m radius. Sometimes lions may have killed emaciated and lethargic buffalo, whilst in other cases they may have been scavenging on buffalo that died directly due to starvation or other drought related processes (photo: Izak Smit)

- A decline in black-backed jackal was noticed by the Tshokwane section ranger since the early 2000s and also an increase in side-striped jackal. Although the black-backed jackal numbers seemed to have increased over the years leading up to the drought, it seemed as if the past drought may have boosted them even more – on one occasion 23 black-backed jackal were seen on a single rhino carcass during the drought. Side-striped jackal may have been disadvantaged by drought, as this species is dependent on small rodents, reptiles and berries which may be less abundant during droughts.

- A trails ranger perceived that predator numbers increased, and only started to normalise again in 2019.
- The Mooiplaas section ranger perceived an increase in hyenas observed in that section during the drought.
- In Timbavati Private Nature Reserve to the west of KNP, predators seemed to do well during the drought. Wild dog denning sites were more than usual in the reserve (three, most years maybe one), and one pack was comprised of 30 individuals. Lion seemingly favoured the areas close to the boundary between KNP and Timbavati, where they would ambush buffalo moving between KNP (possibly for food resources) and Timbavati (possibly for water resources), with the other predators (leopard, wild dog and hyena) focusing their activities on the central part of the reserve (away from lions). An interesting observation included leopard and spotted hyena seen feeding on the same carcass without showing signs of rivalry, as well as spotted hyena and black-backed jackal. This is most likely due to the abundance of food.
- African civet in poor condition were reported on a number of occasions during day time in rest camps or approaching vehicles (Figure 19). These animals behaved in an "unusually tame" manner, and raised suspicion of rabies – however, no cases of rabies were noted by State Veterinarians, and this behaviour is most likely due to malnutrition.

Figure 19: Multiple observations of "tame" African civets during day-light hours were reported (Photo provided by Louis van Schalkwyk

4.3.2. Birds

- General patterns:
    - Less bird species diversity observed (particularly among migratory species) and less abundance of certain species (see below).
    - Bird community surveys (southern basalt supersite) suggested a turnover in dominance of mainly insectivorous bird species, as well as a decline of seed dependent species during the drought.
- Unusual sightings:
    - Some bird species were recorded in KNP that do not normally occur here or are rarely observed (e.g. Marico flycatcher *Bradornis mariquensis*, red-capped lark *Calandrella cinerea*, Narina trogon *Apaloderma narina*, pink backed pelicans *Pelecanus rufescens*, European wheatear *Oenanthe oenanthe*, Lesser Jacana *Microparra capensis*, Mountain Wagtail *Motacilla clara*, Blue-mantled Crested Flycatcher *Trochocercus cyanomelas*), whilst some usually common species seemed less common (e.g. fewer water birds, wattled starlings *Creatophora cinerea*, large migratory eagles, migratory storks (like White Stork *Ciconia ciconia*)).
    - During the drought there were sightings of rare birds (not clear whether coincidental or not):
        - Narina trogon (Phalaborwa section ranger garden; November 2016)
        - Large flocks of Pelicans on gravel road between Olifants and Letaba, Engelhardt Dam and Mingerhout dam (about 100 individuals in total) (25 February 2016).
        - European wheatear (Transport dam) (first noted 26 November 2015, but only reported in wider birding circles by 11 December 2015) (based on information provided, it seems as if this is the first

ever record for KNP, and that this species has been observed <20 times in southern Africa).

- Outbreaks:
  - Massive red-billed quelea swarms were observed for a couple of weeks around southern and central KNP in the first summer post drought (2017) (Figure 20) – many birds of prey were seen perched on trees feasting on these birds. The massive flocks of birds returning to their roosting areas in the reeds of the Sabie River and Lake Panic in the late afternoon were particularly spectacular and have not been observed before by colleagues with more than 38 years' experience in the park. These massive quelea swarms certainly have not been noticed in the Sabie River since 1960 and written records before that also make no mention of them. This was one of the most noticeable and vivid post-drought eruptions, comprising of hundreds of thousands of birds. Birds of prey were attracted to these quelea outbreaks, and large numbers were often seen perching in trees in the vicinity of the swarms (one colleague also mentioned that many falcons, including Lanner and Peregrine falcons, were also often observed in association with the queleas, whereas usually only one or two Lanner falcons are typically observed in a year by the colleague).
  - High numbers of owls were observed during the rodent outbreak after the drought. Areas and species specifically noted were grass owls on the basalts in Lower Sabie section and spotted eagle owls, especially on the Skukuza – Pretoriuskop road at night.
- Behaviour:
  - Crowned hornbills were seen eating fleshy leaves of *Aloe parvibractifolia* (in Skukuza staff village). Although they have been observed and are known to forage on fruit and seeds of these plants, there does not seem to be a record of them eating the fleshy part of aloes and they have never been observed engaged in this behaviour in this specific garden in all the years before.

4.3.3. Rodents

- Rodent outbreaks after the drought were widely observed and reported, especially around Lower Sabie, Skukuza, Satara and Nwanetsi sections. This outbreak caused damage to camping equipment of guests to the park, as well as to infrastructure (author of this report had damage to vehicle where rodent gnawed wires and plastic pipes).
- Rodent surveys (around southern basalt supersite) reported a decline in species richness from 6 species to 2-3 during the drought (although hard to attribute to drought alone). Trap success, an indicator or activity and abundance, declined dramatically from c.a. 40% before drought to 5% during drought (5% is actually the mean for savannas). Trapping success rebounded to close to 80% in the two winter seasons following the drought. The third winter after the drought (2019), the trapping success reduced again significantly to 10-30% per grid, and the other species started to creep back in. By far the greatest proportion of the outbreak was ascribed to *Mastomys natalensis* (although *Mastomys* is treated as a complex, as it is virtually impossible to tell the species apart in the field). It is anticipated that there was a change in ecosystem services associated with these declines and subsequent recovery e.g. seed predation and dispersal, prey for larger vertebrates and nutrient cycling.
- Letaba section ranger also noted high numbers of what seemed like *Saccostomus campestris* (Pouched mouse) (April 2017).
- Nwanetsi section ranger reported trapping up to 76 rodents per night in the staff quarters.

4.3.4. Spiders

- Massive apparent decline in the Golden and Garden Orb spiders. Colleagues reported walking into webs whenever in the field during summer, yet over the past three summers since the drought it was really hard to find any webs or spiders even when looking for them. One colleague mentioned seeing probably only four in the past summer (2018/2019), whilst he used to be covered in spider webs each time doing fieldwork around that same area in the past (i.e. the Letaba exclosure close to Phalaborwa).

4.3.5. Reptiles

- Various colleagues mentioned a reduction of snake observations during the drought and possibly a slow recovery afterwards.
- From SAEON reptile surveys in the Phalaborwa area, it was observed that snakes, chameleons and tortoises were particularly hard hit by the drought, with few of these observed in 2017 and 2018, compared to 2015.

- Flap-necked chameleons (*Chanaeleo dilepis*) have not yet recovered even 3 years after the 2015/2016 drought – in places where chameleons were seen very frequently on drives at night, it is a rare and notable occurrence in 2019 – there seems to be little or no chameleons left in certain areas and the post-drought population recovery seems slow.
- Snakes were also affected, and especially large snakes are still rare three years after the drought as they seemingly perished during the drought (i.e. black mamba *Dendroaspis polyepis*, Mozambique spitting cobras/mfezis *Naja mossambica*, puff adders *Bitis arietans* and African rock pythons *Python sebae*). Recovery has been rather slow and only in 2019 did snake observations start increasing again.
- Nwanetsi section ranger reported that skinks (rainbow and blue-tailed) have seemingly become more abundant in and around human habitations (staff accommodation) after the drought – one can speculate that it is partly linked to reduction in predation pressure by snakes (see response of snakes above).
- Crocodiles have dug caves in banks over the past 2-3 years after water levels in pools/springs have dropped too far to cover them – even as many as 5-6 large crocodiles sometimes share the same small cave (Nwanetsi section). The crocodiles are still active and move in and out of the caves, and it would be interesting to monitor them and determine whether they become fully dormant if rain is not received to fill the pools again.

Figure 20: Massive swarms of several thousand red-billed queleas were seen in southern and central KNP in the summer after the drought – this was one of the most noticeable post-drought eruptions with ~30 minutes of constant flying of swarms of thousands of birds returning to sleep in the reed beds along the Sabie river and Lake Panic late in the afternoons (photo: Marna Herbst).

4.3.6. Invertebrates

- There was a widely reported reduction in insects and other invertebrates observed during the drought and in the three years subsequent to drought. Lack of insects on windscreens after driving at night, and lack of insects around outside lights, was noted by a couple of respondents. A couple of more specific examples include:
    - Hardly any armoured crickets for past three years since the drought
    - Hardly any dung beetles observed during the drought, but they responded quickly in 2017 after rains returned.
    - Past 3 years hardly any moths around lights at night.
    - Very few (if any) millipedes observed during the drought (this may link to poor conditions of African civets noted in 4.3.1.7. and Figure 19).
    - Experienced lower levels of mosquito abundance during drought.
    - The small black stink bugs *Geocnethus plagiata* (one of the ground burrowing bugs) that used to swarm around lights at night during summer (after the first good rains) and which is generally seen as a pest, were

conspicuously absent during the drought. During the past two summers however their numbers have been increasing significantly.

- Mopane worms in the Phalaborwa area seemed to suffer a complete collapse. Outbreaks were few and far between and not particularly large where they occurred. This was the case both inside and outside of the park, although outbreaks were already less common around villages before the drought. Nevertheless some outbreaks did occur, in response to the occasional good rains, and sometimes at unusual times (e.g. outbreak around Makhuva village in late May 2016, whilst the feeling is that it is usually in March to early April). Timing of rain seems to be more important than amount of rain. If the soil is too dry when the worms reach their final instar, and come down the trees to bury themselves, then it seems they die on the soil surface. So enough rainfall to keep topsoil moist in mid-December and late March seems key. Only a few days or a week of wet soil is needed for the mature worms to get down the trees and bury themselves. So if you have a dry spell at those times it could be disastrous for that cohort. Food supply for worms was not an issue as mopane trees had canopies full of leaves throughout the drought summers, and the trees hardly suffered any mortality.

- It is not clear how termites and their impacts responded during droughts. A perception was expressed that the effect of termites becomes larger if it is drier, but it was also acknowledged that this may just be a case of the impacts of termites becoming more noticeable during dry periods. Increased winter temperatures during drought may possibly also increase termite activity. During the 2015/2016 drought, termite effects on basaltic derived soils seemed to have been higher compared to the effect of termites on other landscapes like granites and ecca shales. The effect of especially non-mound building termite species is believed to be important.

- The debarking of *Dichrostachys cinerea* by termites occurred extensively within Wits Rural Facility between October 2016 and mid-2017 (Figure 21). Termites of the genus *Odontotermes* (Macrotermitinae) seemed responsible – a fungal-feeding termite with subterranean nests. Over this period it was observed that within large stands of *Dichrostachys cinerea* not a single tree remained untouched by termites. In the years that followed this same phenomenon was observed but only in small patches. Afterwards when the sheeting has been washed away it was clear that the trees were debarked. Many of these trees died following debarking (confirmed by cutting trees with a machete). Many of the dead trees remain standing for a long time following debarking as the wood is termite-resistant and often used by farmers to construct fence poles. This phenomenon may have also occurred in some areas of KNP, but was not reported and as such not widely observed (at least not by the author who only saw it at a couple of locations).

- Various insect eruptions were noted, either post-drought e.g. a black stink bug (*Strombosoma impacta*) that had a large outbreak in Mopani camp causing a nuisance to staff and tourists alike (end of February 2017), or during the drought such as banded Achaea (*Achaea catella)* during February 2016 (Figure 22).

Figure 21: Termites of the genus *Odontotermes* (Macrotermitinae) were seen building sheeting on *Dichrostachys cinerea* (left), and debarking the tree as can be seen when the sheeting came off (right) (Photos: Katherine Gordon).

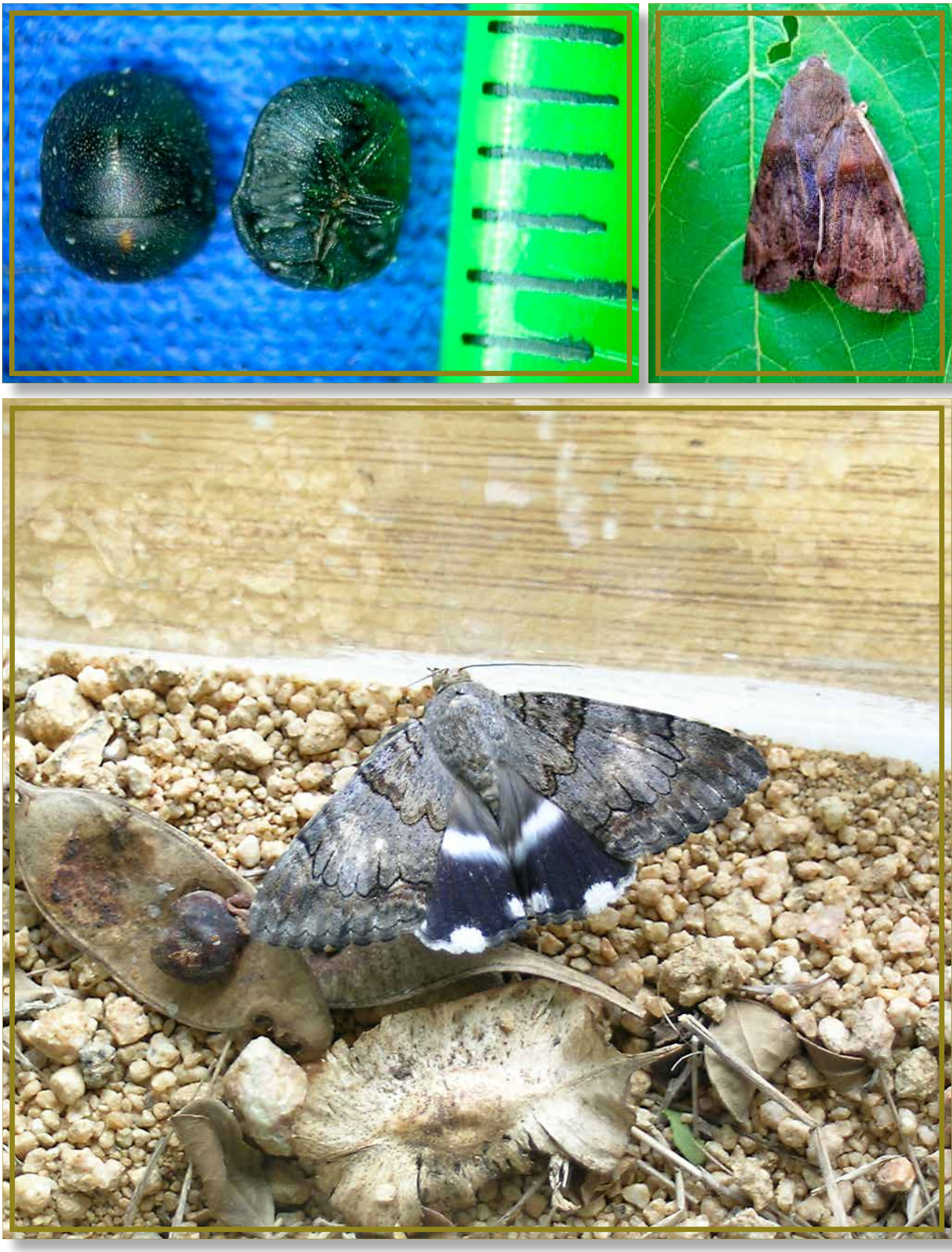


Figure 22: Various insect outbreaks occurred in the year after the drought, including e.g. a stinkbug *Strombosoma impacta* (top left)*;* this species had an outbreak at Mopani camp following the drought and became a big nuisance for tourists and staff. During the drought, the banded Achaea (*Achaea catella)* also had outbreaks and large numbers of them were flying around and noted around Skukuza staff village (top right and bottom) (Photos: Guin Zambatis).

4.3.7. Other taxonomic groups

- *Freshwater jellyfish:* Although hard to attribute to drought, the first ever record of freshwater jellyfish (*Limnocnida tanganjicae* – Great Lakes Jellyfish) was recorded in KNP at the peak of the drought (October 2016 at Red Rocks in rock pools in the Shingwedzi river) (Figure 23). The second ever record was noted two years later in November 2017, again at the end of a dry and warm winter and in rock pools of an ephemeral seasonal stream (Bangu spruit, tributary of Olifants river >100 km from first location). The Great Lakes jellyfish is better known from further north in Africa and occurring in large lakes rather than small rock pools.
- *Tarebia granifera* (a south-east Asia member of the freshwater prosobranch gastropod family Thiaridae): In-stream density of this invasive aquatic snail increased in the pool and backwater habitats in the Sabie river during the extended periods of low summer flows experienced during the drought. Notable declines in snail densities were observed again in 2017 and 2018 as high seasonal flows may reduce local densities through downstream displacement of individuals and reducing population growth rates in this parthenogenetic species.
- Notable *Euglena sanguinea* algal blooms were observed in isolated pools in Sabie Poort (April 2016) as well as in the Mhala Mhala spruit, Letaba section (July 2017) (Figure 24). These blooms are not necessarily uncommon, but may be more prevalent during droughts as water bodies/pools get isolated, with increased temperature and nutrients, creating conditions conducive to these blooms. These blooms have been associated with fish deaths in the past in other areas (Zimba et al., 2010).

Figure 23: Freshwater jellyfish were recorded for the first time in KNP during October 2016 during the height of the drought in the Shingwedzi river at Red Rocks. They were recorded again at Bangu potholes in November 2018, after another warm and dry period (photos: Izak Smit)

Figure 24: Notable *Euglena sanguinea* algal blooms were observed in isolated pools in Sabie Poort (April 2016) as well as in the Mhala Mhala spruit, Letaba section (July 2017). These blooms are not necessarily uncommon, but may be more prevalent during droughts as water bodies/pools get isolated. This algae forms a thick velvet-like "mat" on water that turn red from a unique pigment in their cells (astaxanthin) which acts as a kind of sun block should light exposure become too great - the colour of the cells can change back to green (photos taken at Mhala Mhala stream; Andrew Desmet).

4.4. General animal behaviour

- Changes in animal emergence times were observed during the drought, probably to extend feeding time. It was obvious for hippos grazing outside of their normal nocturnal feeding hours, but it also seemed true for bats (earlier emergence) and birds (earlier dawn chorus).
- Based on a "felt barometer", colleagues on foot expressed that they experienced increased animal aggression – especially near water. An experienced trails ranger noticed for the first time panic once they approached a small buffalo herd in poor condition with signs of aggression from the cows. It is unclear whether this may be due to animals being more stressed in general and/or due to increased intra and inter specific competition during drought periods. One can also appreciate that the "flight response" of animals in a weakened condition might be retarded and this could allow animals to be approached closer than usual which then could trigger the "fightresponse".

4.5.1. Animal Diseases

- It is very difficult to make direct links between disease occurrence and drought, although malnutrition always has linkages to impaired immunity, and thus potential disease/disease-related mortality. Furthermore, the concentration of animals around scarce water and food resources increases intra/interspecies contact rates, which could also play an important role in the extent of disease spreads compared to normal conditions.
- There has been active surveillance for tuberculosis (TB) for years in the park, but during the drought period it was the first time that clinical cases of TB were found in white and black rhino, as well as elephant. Also, subsequent to drought, the TB cases have seemingly tailed off again:
    - During the drought the first ever record in KNP history that white and black rhino died of or were dying of bovine TB (compromised rhino that were euthanized had clinical TB; Miller et al., 2018). It was often emaciated animals, with emaciation rather due to malnutrition or injuries than the disease (lesions very small). It is possible that the drought could have exacerbated the disease, or just made detection of emaciated/sick animals more likely.
    - A single elephant was also found to have lungs full of human TB (first time ever for free roaming elephant) – this is most likely coincidental and not necessarily attributed to drought (Miller et al., 2019) (Tshokwane section).
    - Bovine TB was also found in a number of wild dogs during post mortems (including those that died of distemper – see later) – ante-mortem testing also revealed a high apparent prevalence of the disease in wild dogs (Higgitt et al., 2019) – again, this can be coincidental and it is hard to attribute to drought.
- Black-backed jackal, lion and wild dog with mange reported a few times (S28, Ngotso North, Satara, Nhlanguleni, Sabi Sands Wildtuin):
    - Often the same animal(s) reported numerous times – perhaps they were more visible, or else they stayed close to roads for easy food (e.g. roadkill in case of jackal) (Figure 25).
    - Lion cubs often most affected.
    - Jackal numbers seemed "good to high" during the drought – mange is generally stress-related in adult animals (all jackal with mange that were reported were adults) – possible causes may be social, interspecific or nutrition related.
- A number of elephant mortalities were reported and investigated after the drought that created suspicion of encephalomyocarditis (EMC) – none have been diagnosed, but given the explosion of rodents (carrier of EMC), it was very likely the cause of death in elephants.
- Wild dog mortality due to distemper was observed during the drought for the first time since Wolhuter's time (see "Memories of a Game Ranger" by Wolhuter and also Ndaimani et al., 2016). The entire pack succumbed along the Sand River (Tshokwane section). It is unclear whether this might have been coincidental or might be drought related. Perhaps the wild dogs were under more stress than expected for a predator during drought, making it more susceptible to disease-related mortality that might generally occur sub-clinically (retrospective study in 2009 found 78% wild dogs sero-positive to distemper, but no mortalities reported).
- Mass-mortalities of laughing doves reported in Madimbo Corridor, Houtboschrand, Skukuza and Pretoriuskop – related mortalities in Mpumalanga diagnosed as Pigeon Paramyxovirus (closely related to Newcastle disease) – mortalities generally around water points where large flocks of doves would congregate – most likely unusual densities due to scarcity of water and thus indirectly drought related.
- Strangely enough no typical dry season anthrax outbreak occurred (compared to 1991/1992 drought when there was a large outbreak) – conditions were considered ideal for it based on previous outbreaks. There were only a few

isolated anthrax cases during 2015/16 drought and also in species like hippo, an animal not historically associated with anthrax mortalities in Kruger NP.

- Emaciated animals and even mortalities were observed after the rains returned. No diagnoses were made in these cases, but it could possibly be due to Clostridiale disease that is often associated with so called "green drought" (especially for grazers). Animals are still in a catabolic state due to protein shortage after a drought. The new green vegetation is low in protein and high in carbohydrates and moisture, and the colon bacteria is not yet adapted for this, so the animal still suffers to extract energy/protein from the forage, and as such continues to suffer from malnutrition even though there is apparently an abundance of food.

Figure 25: Mange in various predators were more frequently reported during the drought period (Photo provided by Louis van Schalkwyk)

4.5.2. Human health

- Higher prevalence of malaria reported in KNP in year after drought (2017). This may possibly be due to "predator release", with the mosquitoes breeding fast in the first year after a drought, whilst mosquito and mosquito larval predators are slower to recover in order to "control" mosquito densities.

4.6. Water resources and hydrology

- The perennial rivers flowing through KNP were very actively managed at a catchment scale during the drought (Figure 26). This was mostly through daily monitoring of flow rates, which resulted in consultation at high political levels (up to Director General level at Department of Water and Sanitation). River management interventions centred around releases from large upstream dams and abstraction restrictions (up to 80%) across the irrigation sector (domestic and industrial sectors were also restricted but at lower levels, but not at all in some catchments where government's bye-laws delayed this). The flows of perennial rivers in KNP were generally higher/better than observed during the

1991/1992 drought. The Letaba river stopped flowing for months downstream of Engelhardt dam, but had pools throughout its length. The Sand river also stopped flowing for most of the hydrological year.

- The hydrology of the lower Olifants River is interesting and dynamic due to the influence of Massingir Dam in Mozambique. The Olifants gorge below the confluence with the Letaba River has been silting up after the water level in the dam was raised in 2008. During the past droughts almost the entire Olifants gorge from about 1 km below the confluence with the Letaba all the way to the Mozambique border had silted up. Interestingly the 2016/17 summer rain season was a "normal" rainfall year without excessive flooding of the rivers flowing through the Kruger NP. Both the Olifants and Letaba rivers had peak summer flows of around 330 cumecs. The higher a river flows the more energy the water has to suspend sediments and this is why we have seen massive sediment deposits during severe floods where the water is forced to slow down like where it enters a dam. It is thought that the low water levels in Massingir Dam due to the drought conditions and "normal" summer flows created a situation where the Olifants River flushed all the sediments out of the Olifants gorge and again created a deep-water habitat.

Figure 26: Flow in the Olifants River during height of drought was about to cease (<0.4 cumecs when photo was taken on 6 September 2016) (top), but a water release from the upstream De Hoop Dam ensured better flows across the entire stretch of river below the release (bottom photo was taken end of October 2016 after release from de Hoop dam on 14 October 2016, resulting in improved flows of ~2 cumecs). The Association for Water and Rural Development (AWARD) played a critical role in these processes and was a key partner with SANParks and other stakeholders during the drought (Riddell et al., 2016).

- Most artificially created earthen dams dried up as they were not connected to groundwater. This is problematic because large hippo and plains game populations that built up in and around them during years in between severe droughts have to move to other water sources, putting additional pressure on those receiving areas. This caused large concentrations of hippos in some smallish pools, e.g. the almost dry Orpen Dam near Tshokwane (see section 4.10 for more details). In addition, the dried up dams usually acted as mud traps for other animals coming to drink here.
- It was noticeable that even though rainfall was low, water was present at various pools in seasonal rivers and springs and seemingly very few large mammal mortalities could be ascribed to water shortages (Figure 27). The exception may have been hippos where pools shrank and less dominant animals might have been pushed out to unfavourable habitat that could have resulted in mortalities. As such, many colleagues indicated that mortalities of mega herbivores were due to lack of food, not lack of available surface water resources (see section 4.2.).
- Timbavati Private Nature Reserve noticed large footpaths from KNP to dams in the Timbavati closest to the boundary, and suggested that animals utilised KNP for grazing resources and Timbavati for drinking resources. Lions also exploited this movement by focusing on these routes between forage and water with high movement activity of buffalo. The increasing distance between forage and food resources impacted the buffalo, and possibly also white rhino.
- Elephants and rhinos played a critical role in exposing water by digging drinking holes in dry riverbeds and at springs for many other species (Figure 28).
- Although it was noted that some springs dried up during droughts (e.g. Malonga fountain in Pafuri, 2018/2019 drought), many others remained surprisingly reliable (Figure 27). One trails ranger indicated that some springs remained strong, and indicated that in his experience some springs may have even become stronger rather than weaker during the drought. Another colleague also confirmed that this was mentioned by Dr Tol Pienaar, an established KNP warden, during previous droughts. There is no data to support or refute the "strength" of the springs during the drought, but it may be speculated that hydraulic lift can possibly contribute towards this when vegetation evapotranspiration is reduced. Alternatively, it has been argued that there can be time lags between rainfall events and recharge to be noticed in certain areas due to slow subsurface flows.
- During the drought, water was observed to remain in tributaries of larger rivers and as pools in seasonal rivers (e.g. Shingwedzi river, Biyamiti river, etc.) (Figure 29). It was also interesting to note how these pools were not randomly located but occurred in areas where pools often remain during the dry season – section rangers from a couple of years back could accurately "predict" where water would be found based on past experience of where water always remains. Some of these pools may have acted as important refugia, and massive numbers of small tilapia fish were observed in some of these pools after the drought (Figure 30). This reaffirms the importance of groundwater resources during droughts as they play a critical role for sustaining ecosystems during droughts and creating refugia (most likely also for riparian trees on banks of the seasonal rivers, with these trees acting as important resources during drought for other species dependent on them for shade, food, nesting, etc.). Groundwater was clearly less affected than surface water sources and acted as a slow responder and buffer during droughts.
- Based on a long-term groundwater level monitoring project, it has been observed that groundwater levels have been dropping gradually in the south and central parts of the park due to the current dry cycle. This pattern is typically linked to the 8-12 year climatic (i.e. rain) cycles. In the Nwanetsi section it was noted that in 2019, the springs and rivers were drier than during the 2015/16 drought when they still contained relatively good water levels. It is argued that the dry conditions that have prevailed over the past couple of years have dropped the groundwater level, with some rivers and springs drier than can be recalled for past 40 years (e.g. Mavumbye stream has stopped flowing, with only small springs remaining). This apparent drop in groundwater level has cascading effects on various taxanomic groups (e.g. increased tall tree mortality 3 years after drought, crocodiles digging caves as water level in pools drop - see section 4.3.5.).
- It seems as if there are more flash floods during droughts for the amount of rain (possibly caused by an increase in runoff from bare ground) and this can possibly result in many dams further silting up and possibly even washing away in KNP (one respondent predicted that most dams in Kruger will have washed away in 50 years' time) (Figure 31).
- During the 1991/92 drought the Mpondo dam almost dried up. In February 1993 a local rain storm fed the dam and many barbel fish started swimming upstream. The water however ran off quickly leaving many of them stranded and dying on dry sand in the Mpondo spruit. This phenomenon was also noticed in Reënvoel dam in about 2010.
- Various observations were made during the biodiversity monitoring on rivers pre and post drought:
    - Fish seemed more "concentrated" in the remaining waters in the rivers (i.e. higher catching success) – this was probably due to lower volumes of water available. The fish species caught as part of monitoring during the drought appeared normal (i.e. same species as is observed during "normal" years), with the exception of some species that seemed to experience large "outbreaks" during the drought (although it may possibly also be due to sampling efficiency differences):

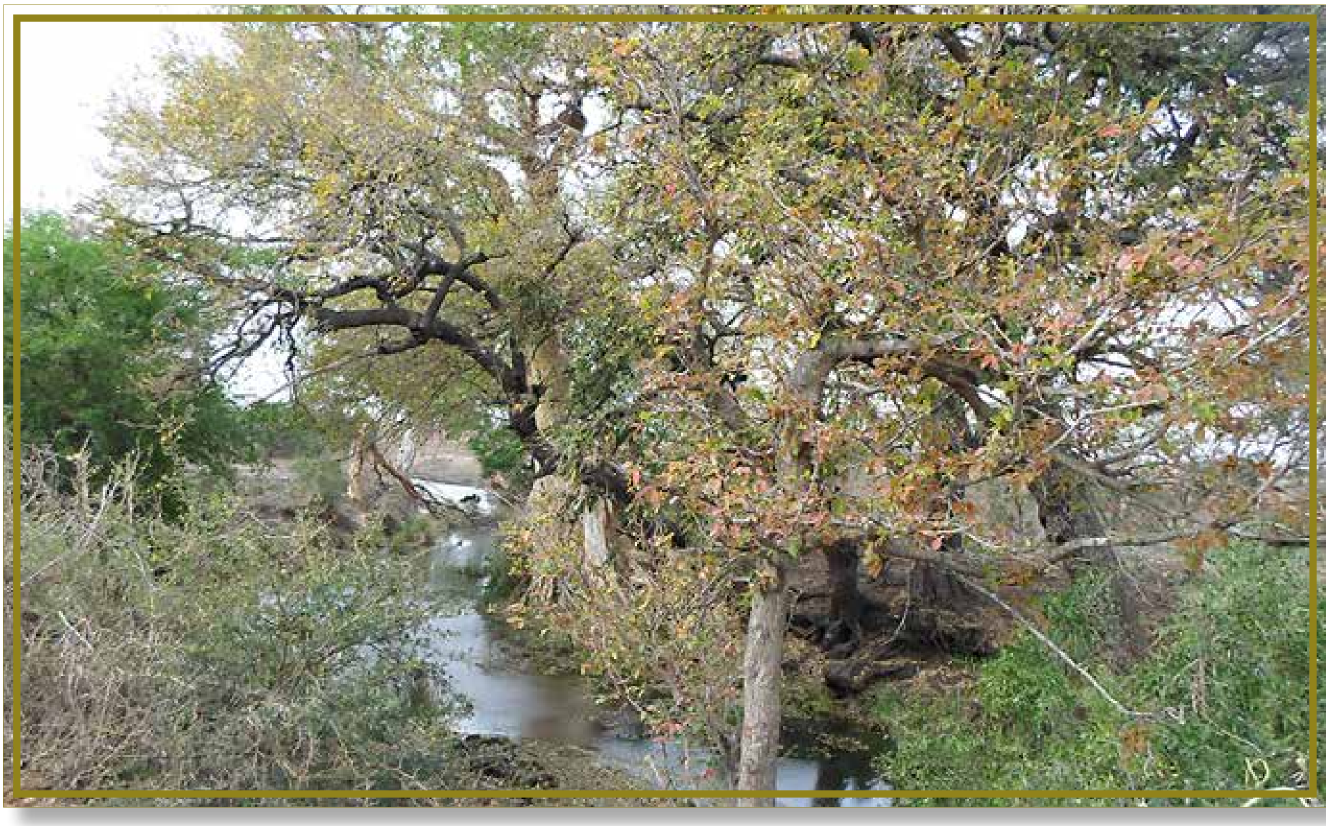


Figure 27: Many springs continued to be very reliable water sources during the drought, even at the epicentre of the drought, e.g. spring along Gudzane spruit (S90) (top) and Nyamarhi spring in the Ngotso spruit (H1-4) (photos taken September 2016 during height of drought; photos: Izak Smit).

    - Sabie River: *Opsaridium* were caught in much higher abundance during drought than normal years – the year after the drought this species was back to "expected" levels experienced during normal years.
    - Letaba River: Three spotted barb caught in much higher levels in nets during drought than in other years – due to time constraints researchers could not even count the number of individuals so abundant were they – as above, the first year after the drought, the abundance levels seemed to have dropped back to "normal" levels.
  - The SASS5 indices based on macro invertebrates declined during the drier years (2014 – 2018) at the Sabie and the Letaba rivers compared to the non-drought years (2010 – 2013) while the Luvuvhu river was not affected by the drought. Although an improvement of SASS5 indices was observed on the Olifants River between the wetter and drier years, it is suspected that the improvement is mostly attributed to the improvement of anthropogenic activities upstream, or the fact that the surveys were done after water releases were done from De Hoop dam upstream (pollution from tributaries may also have been reduced). The drought influence on the Crocodile river was not clear. As with many of the other biodiversity monitoring, it is hard to attribute changes to droughts or not as many factors can change between sampling occasions and inter-annual variability is common. This show how important it is that monitoring programmes be supplemented with studies (e.g. experimental studies) to work out causes of change.
  - Drought conditions often result in low water levels and associated changes in water quality, including elevated salt concentration. Diatom community structures respond to such changes due to the specific water quality requirements of the individual species comprising the community. The Specific Pollution Sensitivity Index (SPI) scores reflect cumulative changes in water quality variables. SPI scores reduced across Sabie, Sand and especially Olifants rivers from 2015 to 2016 probably as a result of poor water quality. These reductions may possibly be linked to reduced water quality resulting from drought conditions. SPI scores on Letaba, Levuvhu and Crocodile river remained largely the same (report available). As with many of the other biodiversity monitoring, it is hard to attribute changes to droughts or not as many factors can change between sampling occasions. Diatom monitoring only started in 2015 so as more data becomes available in future the effect of the dry and wet cycles may become more apparent.
- Nwanetsi section ranger reported that frogs were seemingly less affected than reptiles – grey foam-nest tree frog (*Chiromantis xerampelina*) and African bullfrogs (*Pyxicephalus adspersus*) seemed to be resilient to drought, and large increases of frogs were seen post –drought when rains returned.
- Tadpole shrimps (*Triops* sp.), fairy shrimps (*Anostraca sp*) and Spotted Killifish (*Notobranchius orthonotus*) (killifish observed in the Mtomeni stream in Lebombo mountains) have been observed in the post drought period in the epicentre of the drought (Nwanetsi section), suggesting these species are resilient to droughts.
- Farming activities in areas outside KNP were affected due to low flows in the river and the associated water restrictions that were imposed – this has e.g. resulted in some losses of primarily seasonal workers due to poor harvest (other factors also played a role like sugar tax, Brazil dumping sugar on global market and reduction in subsidy). Loss of farming as a viable activity in areas surrounding the park may increase the "attractiveness" and viability of other land-uses, e.g. mining or residential development. However, there were also cases where clever management, better organization and infrastructure investment reduced the impact of the drought on agriculture (https://www.solidaridadnetwork.org/news/south-african-sugarcane-survives-severe-droughts-due-to-better-water-management).

Figure 28: Elephants and rhinos played an important role in exposing groundwater in seasonal streams which were utilised by various wildlife (photo: Navashni Govender).

Figure 29: Groundwater fed pools persisted throughout the drought, often in locations where they are known to persist during the dry season, like this pool in the Shingwedzi River (photo: Izak Smit).

Figure 30: Remaining pools in seasonal rivers, often sustained by groundwater, played an important role as refugia for aquatic species (photo taken below Biyamiti weir on S114 showing Tilapia; photo: Izak Smit).

Figure 31: Various flash floods were observed during March 2016 when late rains occurred during the drought (photo taken on Nwaswitshaka river March 2016; photo: Izak Smit). The question was raised whether flash floods would be more likely during droughts due to the general lack of herbaceous ground cover, leading to more surface-runoff and potential loss of topsoil and erosion. The sound of air bubbles being pushed out of the dry sand was audible, and the water front moved slowly, even though a short distance upstream of the water front the water was flowing strongly.

4.7. Observations from gardens (mostly Skukuza and Phalaborwa Staff Villages)

- Relentless browsing of particularly kudu, bushbuck, nyala and elephants was experienced in Skukuza staff village gardens, as well as grazing by hippos (Figure 32). Fence breakages, especially by hippo (but also elephant), were almost a daily occurrence, and although widely experienced within the village, particular gardens were seemingly repeatedly targeted/preferred. The average monthly fence and gate breakages next that were reported in the Skukuza staff village for repair during the drought increased four-fold (37.4 breakages/month between January – August 2016 versus background rate of 8.6 breakages/month reported across 59 non-drought months) (Figure 33). The biggest increase in fence breakages during the drought was due to hippos (184 breakages in 8 drought months as opposed to 38 breakages across 59 non-drought months). These estimates are considered conservative as some staff stopped reporting fence breakages as it was almost a daily occurrence at some properties. Some staff members added further strands of wires on top of the existing fence infrastructure in order to discourage browsers from entering gardens, whilst others fixed plastic bags and other objects in an attempt to scare off hippos from breaking their fences. Some of the animals seemed to permanently stay in the Skukuza staff village during the drought and, especially the nyala and bushbuck, became very tame during the drought - one could walk within meters of nyala without them moving away. It was hypothesised that gardens (and possibly other "natural" areas as well) may act as small, but important refugia or sinks for species survival and recovery, also birds, insects and possibly soil organisms, during extreme climatic events like droughts.
- Very high abundance of banded Achaea moths (*Achaea catella*) was observed in Skukuza and Phalaborwa staff gardens during drought.
- In the first wet season after the drought, butterflies were seen in very high concentrations, possibly linked to forb abundance (see various sections reporting on outbreaks after the drought).
- Big insect population crash observed by staff based on their experience of sitting outside at night (also see section 4.3.6.) - absence of specific species otherwise regularly observed like hawk moths and large stick insects were noted. The usual outbreaks of dispersing termites ("reismiere") were also seemingly absent.
- On days of extreme temperatures (>40 degrees Celsius) there were large the densities of insects swarming in the undergrowth of shaded parts in gardens. Walking through these areas the activity (sound and visual activity like flight) of insects was unusual and very noticeable (Figure 34). This never lasted long (1 day typically), and once the temperatures dropped again (still high but not extreme), the insect activity was back to "normal". One got the impression that these dense (and possibly somewhat more moist patches) in gardens acted as refugia during these days of extreme temperatures.
- Calls of frogs that are apparent during normal years, were much reduced during the drought period.
- Fewer large resident geckos feeding on insects at night in and around houses.

Figure 32: Desperate animals turned to gardens in order to obtain forage (right photo: Nwanetsi ranger section, Robert Bryden) and also targeting plants not utilised during normal years (left photo: *Aloe* in garden eaten by kudu; Chenay Simms). Many gardens in Skukuza staff village were "destroyed" by persistent browsing by animals that apparently became resident and dependent on the staff villages.

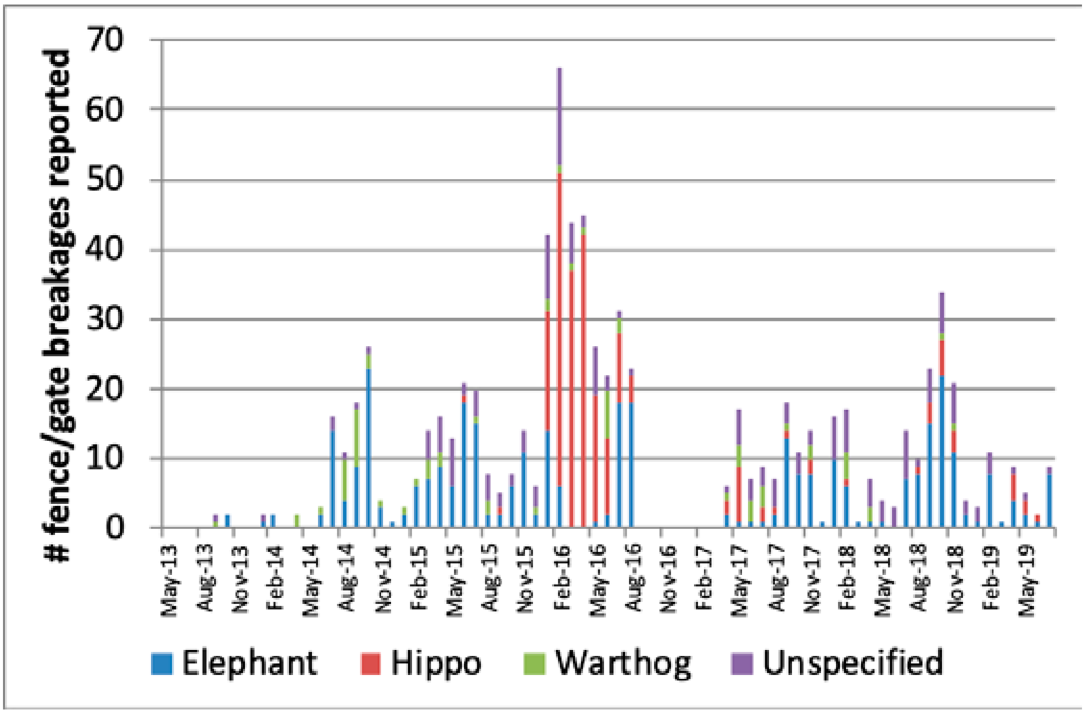


Figure 33: Fence and gate breakages reported to Skukuza Technical Services (no data for period between September 2016 and March 2017 available) (data kindly provided by Poppie Labuschagne, Technical Services, and extracted and analysed by Izak Smit). Notice the steep increase for the period of the 2015/16 drought.

Figure 34: During days of extreme temperature (>40 degrees Celsius) there was noticeably higher insect activity and swarming in undergrowth of dense shaded areas of gardens, e.g. these spider wasps were photographed in a Skukuza garden during one of those days of extreme heat (photo: Ben Wigley).

4.8. Herbivory

- Elephant impact was visible on woody vegetation. This included debarking and uprooting of tall trees, but also smaller bushes (Figure 35). It was also noticed that elephants foraged more than usual on *Dicrostachys cinerea* (e.g. in Malelane section).
- Various grazers were observed browsing and browsers foraging on woody plants they would not normally utilise (one can speculate on the reasons for this, whether they get any nutrients from it or to keep the micro-flora going in the rumen or stomach):
    - Buffalo was observed actively stripping and eating (what seemed like) *Combretum apiculatum* (Figure 36), as well as *Philenoptera violacea*. Buffalo also ate dry leaves of especially *Colophospermum mopane*. Two buffalo bulls waded into the Pioneer dam at Mopani and for most of a day were foraging on the water lilies (Figure 36).
    - Sable was observed browsing on *Philenoptera violacea*.
    - Blue wildebeest was observed eating leaves (Pafuri section 2018/2019 drought)
    - Giraffe was observed browsing on *Philenoptera violacea* (Satara region).

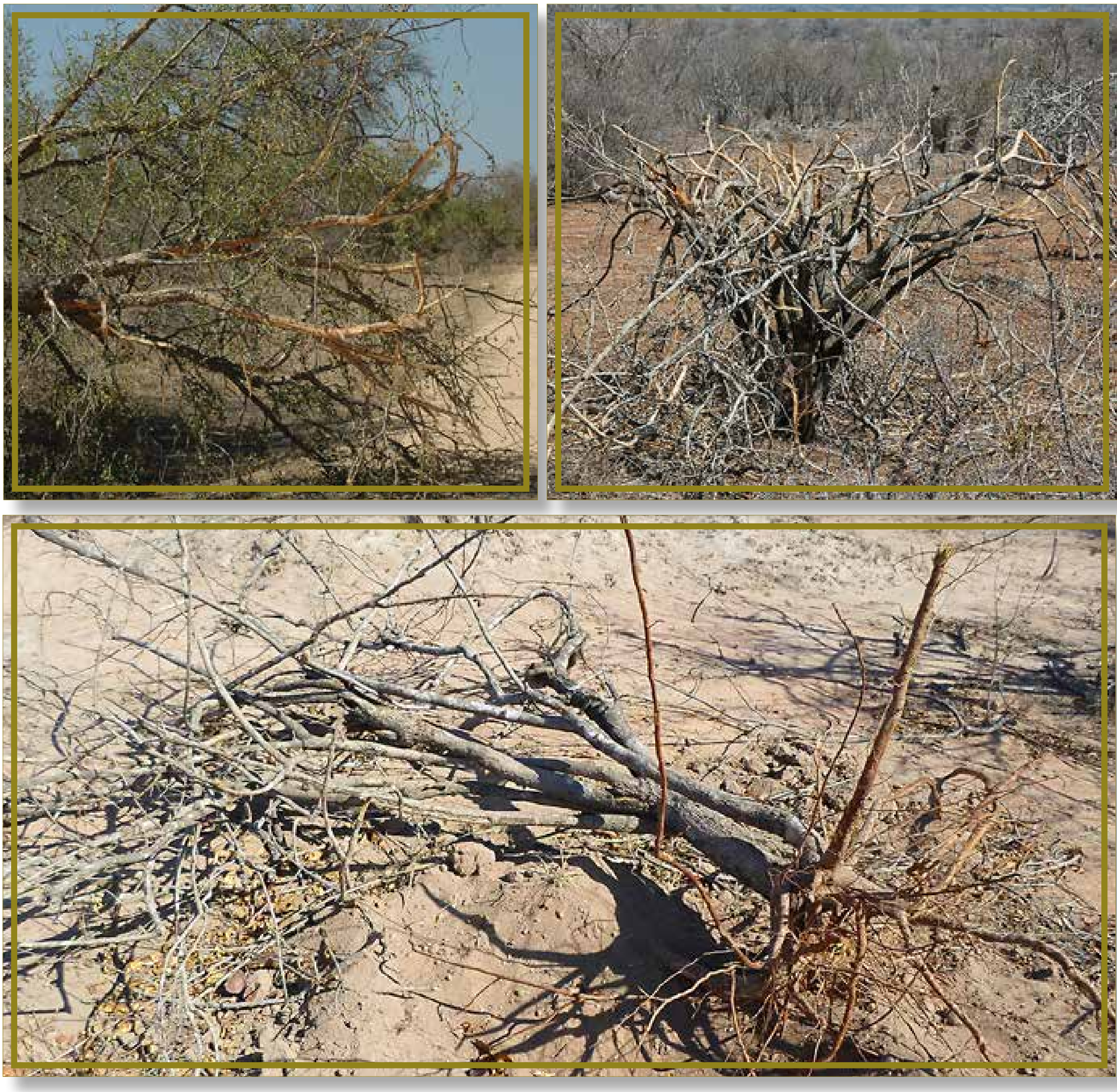


Figure 35: Elephants uprooted shrubs (like *Combretum apiculatum*) (bottom) and increased browsing on certain species not typically heavily utilised (e.g. *Dicrostachys cinerea*) (top right)and also uprooted and debarked tall trees like *Acacia nigrescens* (top left) (photos: Izak Smit).

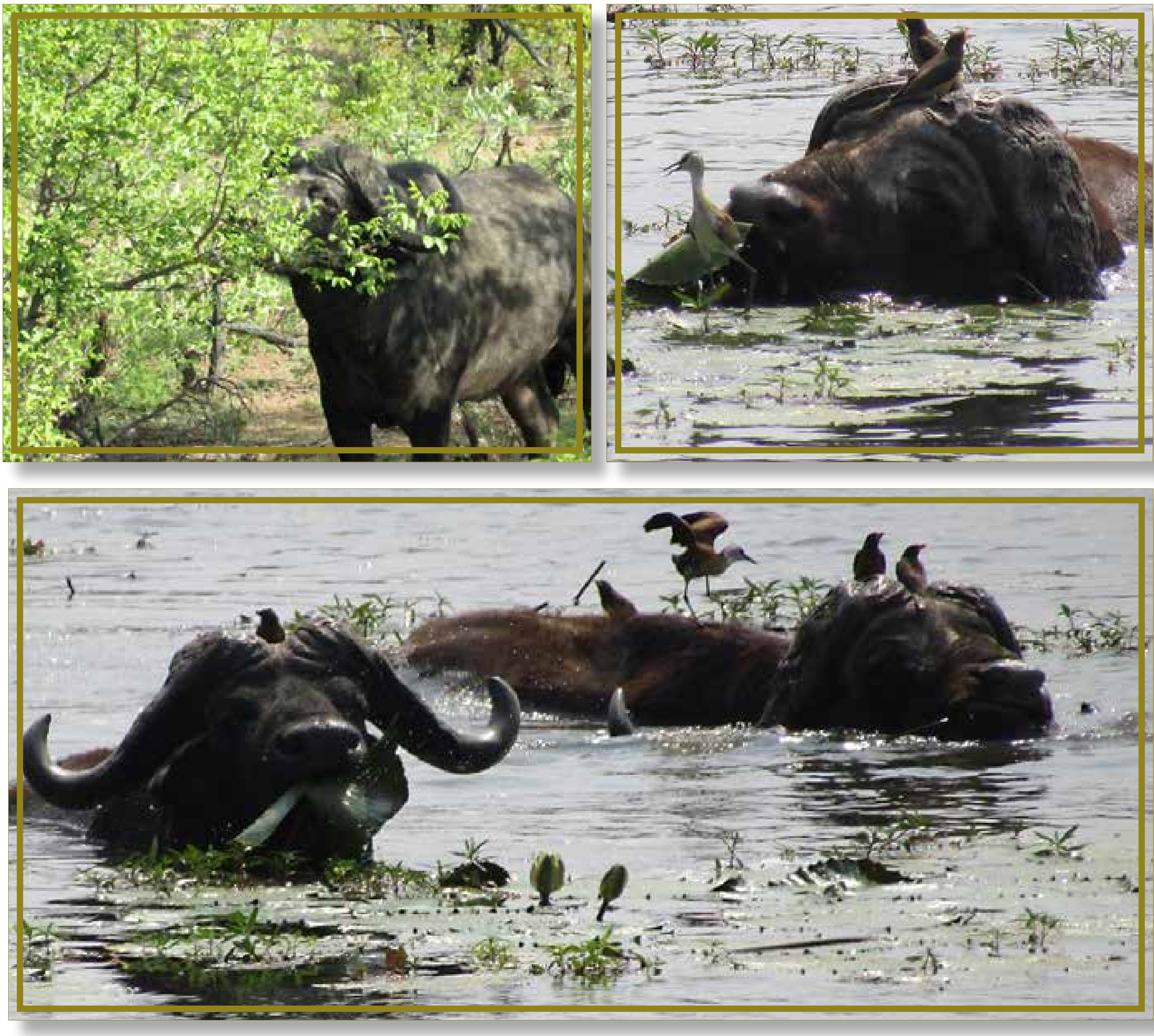


Figure 36: Buffalo browsing (top left) and wading into deep water to feed on water lilies (top right and bottom) (photos taken at Pioneer dam, Twanana) (photos: Jacques Venter)

- The severe shortage of forage for buffalo in Phalaborwa area was highlighted by their grazing of large, dense tufts of *Pennisetum sphacelatum* on the large rock dump of the Palabora Mining Company. Buffalo feed on that dump every year, but usually do not touch this unpalatable, alien species. However, from 2016 onwards, most tufts had been heavily grazed, and it appears that the smaller tufts died from this.
- Higher densities of animals, especially buffalo and elephant, were observed next to rivers – they often browsed on *Phragmites australis* reeds, and would eat the normally dense reeds to short "stompies" (stubble) in some areas (Figure 37).
- The riparian zone on the Crocodile River was heavily utilised by elephants as it became the only water source in the area. An opinion was expressed that water points away from the river should have been opened to prevent/reduce this impact.
- Water run-off from limited rainfall, created some green "fringes" to road (similar to principle of run-off farming), which became resource hotspots for a range of herbivores, including impala, warthog, zebra (Figure 38).
- *Parthenium hysterophorus* stands seemed to have been grazed in Crocodile Bridge section during drought when other food was very limited. It is hard to validate, but some animals have been observed within these dense stands (as well as their dung middens) and *Parthenium hysterophorus* stalks seemed grazed upon (Figure 39).
- The browsing line was very noticeable in certain areas, even more so than in normal rainfall years (Figure 40).

Figure 37: *Phragmatis australis* reeds were browsed to stubble in many areas (Tsendse river; photo: Izak Smit)

Figure 38: Run-off from limited rainfall events created green flushes around roads which were frequented by many herbivores as "resource hotspots", mostly for grazers (impala on H1-3 around Tshokwane (top) and hippo on H1-6 close to Mopani) (middle), but also for browsers (mopani trees flushing on road verge along H1-6 between Letaba and Mopani) (bottom) (photos: Izak Smit).

Figure 39: Although hard to confirm, observations of animals browsing within dense *Parthenum hysterophorus* stands, dung middens and stalks that seemed to have been grazed of at a uniform height provide some circumstantial evidence that herbivores utilized *Parthenium* during drought when other forage was depleted (photos: Thembeka Twala).

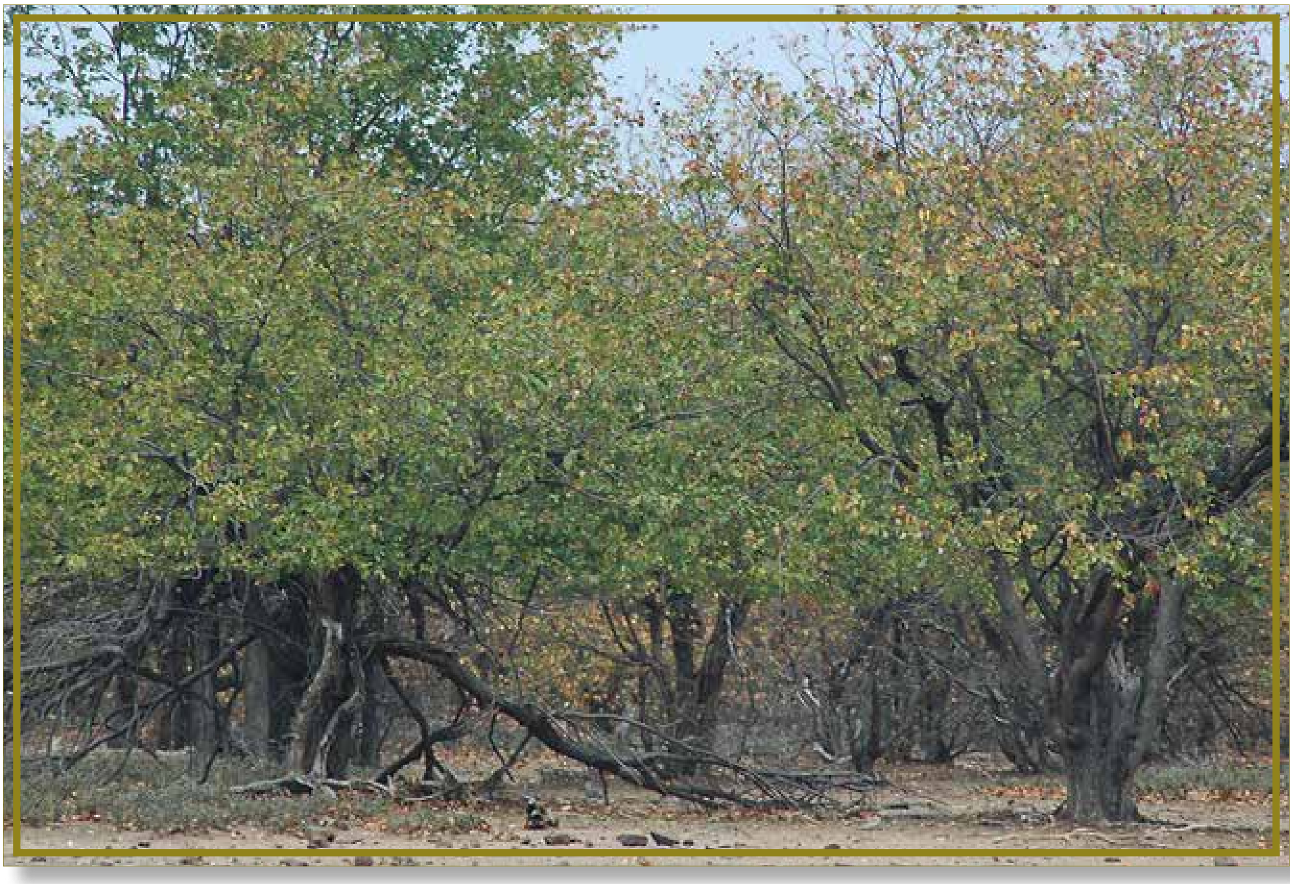


Figure 40: The browsing line became more apparent during the drought (photo close to Letaba; Izak Smit)

4.9. Vegetation

4.9.1. Woody vegetation:

- Since the drought a noticeable mortality of large trees was observed by the ranger in the Kingfisherspruit section as well as a vegetation scientist from SAEON. This included mortality of:
  - a large number of *Acacia welwitchii* (Delagoa Thorns) on ecca shales along the Orpen-Satara tar road (H7) just to the west of Nsemani dam (area that has not burnt for many years and without visible signs of elephant damage) (Figure 41).

Figure 41: Large dead *Acacia welwitchii* trees along the Orpen-Satara tar road (H7) on ecca shales (photo: Tony Swemmer).

  - large *Trichilia emetica* (Natal mahogany) trees along the Timbavati river, and along the tar road where the road runs along the river bank (possibly due to drop in water table). This mortality of large trees on river banks was only really observed in 2018 (details contained in Kingfisherspruit monthly reports) – this may be due to protracted mortality process of these trees, or else a continual decline in groundwater level. In many other locations the dieback from these trees was visible, with large dead branches observed and life part of tree significantly reduced.
- Many large trees (*Combretum imberbe* and *Ficus sycomorus* in particular) were only noticed dying in Nwanetsi section in 2019, three years after the drought, most likely due to the continual drop of the groundwater levels (the area is still in a below average rainfall cycle, so very little recharge and as such a continual drop in groundwater level – see section 4.6.).
- During the 1991/92 drought impacts on riparian trees along the Luvuvhu River was also very noticeable with especially Fig trees and fever trees being affected. It seems as if the water table dropped faster than the tree roots could respond.

Figure 42: *Dicrostachys cinerea* experienced large-scale mortalities over a wide extent, especially in central and southern KNP (photo: Izak Smit).

- The most severe mortality of woody vegetation in the central Lowveld area appeared to be on the basalts in the Nwanetsi section, where large stands of shrubs died, particularly in lowlands close to drainage lines. This was in areas that had not burnt for many years. The majority of these were *Dichrostachys cinerea,* and this also appeared to be the case around Lower Sabie, Crocodile Bridge and Tshokwane where large stands of this species died (Figures 42-43). A number of other species were also affected, including *Combretum apiculatum* around Skukuza and *Spirostachys africana* (across a range of size classes) along drainage lines throughout the far southern and central part of the park (Figure 44). Scattered individuals of *Acacia nigrescens*, of various sizes, died throughout the Nwanetsi and Satara area. Interestingly also a large patch of *Euclea divinorum* (~2 km long by 200-500 m wide patch) died and/or were topkilled during the drought in the Nwanetsi section near Gudzane dam (Figure 45). This is seemingly the first time *Euclea spp* were reported to be affected by droughts. Three years after the drought many of these trees are still completely dead, but with some individuals, especially large individuals or ones next to road receiving rainfall runoff, coppicing. Large-scale recruitment seems prevalent, but not clear whether it is from seeds or root stocks
- Early in the drought high mortality was observed of *Peltophorum africanum* in certain areas in the south (e.g. Stolsnek).
- Seemingly the western-most observation of tree mortality, in the central area of the Lowveld was small patches of medium-sized *Terminalia sericea* that died close to the Southern African Wildlife College. Some large dead trees of this species were also seen on the western boundary road between KNP and adjacent protected areas, just south of Orpen Gate.
- In the Mopaneveld of Phalaborwa and Letaba areas, tree mortality was far less apparent than further south. Some large *Dichrostachys cinerea* died, but most suffered dieback (large branches died, but the trees survived); *Terminalia sericea* almost all survived, despite the high frequency of elephant damage, and the lower rainfall than recorded around e.g. the SA Wildlife College. Some large trees (>10m tall) of *Acacia nigrescens* and occasionally *Colophospermum mopane* and *Combretum imberbe*, without any signs of severe elephant damage, died during the drought. This was also reported in the Letaba section and was also observed in Olifants West Private Nature Reserve. However, these were only a small percentage (maybe 5% or 10%) of the total population of large trees in the area. The most striking mortality north of the Olifants that was observed was of *Commiphora mollis* in the rural rangelands around Phalaubeni (Giyani). It appeared that the majority of these species died in 2016 and 2017. This species is very rare inside Kruger (presumably due to elephants), but mortality of it was also observed in Olifants West Private Nature Reserve (although not as severe as further north, and difficult to distinguish drought impacts from elephant impacts). During the 2018/2019 drought in the far north of KNP (Pafuri region), *Commiphora* plants were also observed dying, and Lebombo ironwood *Androstachys johnsonii* uncharacteristically shedding their leaves.

- A long-term vegetation study on the Satara Experimental Burn Plots (EBPs) has collected data for a number of years before, during and after the drought. During this study a significant reduction in the number of woody individuals was observed between 2015 to 2017. Furthermore, tree species were seemingly less impacted than 'shrub' species (where 'shrub' is defined as something that protrudes minimally from the herbaceous layer, regular resprouter, multi-stemmed via suckering, geoxylic suffrutex ('functional forb')). Some examples that were hard-hit by the drought were *Boscia foetida, Lantana rugosa, Maerua parviflora, Ehretia rigida* and *Ormocarpum trichocarpum*. The impression was that trees were more drought resistant whereas the shrubs were more drought sensitive, with the drought having the effect of opening up the understory. These observations were independent of fire or herbivory treatments.
- Various tall trees died within the Skukuza staff village – some colleagues reported losing as many as four trees in their gardens during the drought. Conservation Management also noted many such dead trees in the Skukuza staff village which had to be removed after the drought due to risk of falling and causing injury or damage.
- Prolific flowering of various plants was recorded at the end of the drought or shortly thereafter, and especially *Acacia nigrescens* was spectacular for about a week before becoming a duller beige in the spring of 2016. *Phragmites australis* reeds also seemed to flower more profusely in years after drought.
- An Mpumalanga Tourism and Parks Authority (MTPA) colleague working outside KNP indicated that especially *Acacia* and *Aloe* species produced lots of seeds after the drought. The impression was also that the seed were less predated, allowing for more seedlings to establish.
- Theory suggests that woody plants may recruit successfully immediately after a drought, given a window of opportunity associated with release from competition from grasses, decline in fire intensity and frequency and decline in herbivory. Resurveys of c.a. 25 transects of tagged *Combretum imberbe*, *Sclerocarya birrea* and *Acacia nigrescens* across the southern Kruger Park towards the end of 2017 and early 2018 as the drought broke surprisingly did not produce a single germinant of any of the three species or any evidence of recruitment during the 3 – 5 year period of the survey. More data on germination, possible release of sapling and post-drought growth spurts are needed to fully understand the role of drought in the recruitment process of woody vegetation.

Figure 43: *Dicrostachys cinerea* die-back visible around Orpen dam (Tshokwane section) when rains returned with dead trees and topkilled trees clearly visible (photo: Izak Smit).

Figure 44: Stands of dead *Spirostachys africana* were noticeable in various locations.

Figure 45: *Euclea divinorum*, an otherwise very hardy plant, also displayed mortality and top-kill during the drought in the Nwanetsi region – this has not been noted during previous droughts in KNP (photo: Danie Pienaar).

4.9.2. Herbaceous vegetation layer:

- The total lack of herbaceous biomass over large areas was very striking and noticeable (Figures 46-47) – as well as the incredible seed bank from which the herbaceous layer re-established immediately after the rains returned (Figures 48-49).
- During the drought more grass biomass was observed in the north than in central parts of the park – this reflects the differences in rainfall experienced between the north (higher rainfall) and south (lower rainfall) during the drought (this is the reverse of the long-term rainfall gradient). Colleagues that flew aerial surveys indicated that the area between Lower Sabie and Mlondozi felt like flying over the Kalahari due to the red sands and no sign of grass for kilometres (Figure 46).
- Large areas which were bare ground during the drought turned into areas of high fuel loads after rains returned, especially in the central parts. Some were of the opinion that the biomass post drought was even higher than during pre-drought (this can likely be tested using existing VCA data) (Figures 48-49).
- Massive forb emergence was noted during drought when small rainfall events occurred and also directly after the drought (especially between Skukuza and Satara) (Figures 50-51). Also, area around Ngotso, south of Olifants river, had a massive flower bloom after the drought and a high associated biomass. Forbs are known to be the first in the herbaceous layer to make use of sudden increases in soil moisture within/after a drought event. However, not all forb species make equally use of this 'window of opportunity' (Siebert and Dreber, 2019). Forb responses to extreme events, such as a drought, is very species-specific.
- *Albuca seineri* and *Ammocharis coranica* blooms were very visible after drought (Figure 52). These blooms are observed most years, and it is unclear whether the blooms were really more prolific after the drought, or possibly just more visible due to the lack of other vegetation. *Crinum minimum* was discovered in bloom on the Phabeni road (0.78km NE of the S65) (Figure 53). Long-serving botanists in the park, who discovered them (Guin and Nick Zambatis) have never seen them before in the park – it is a new locality for this plant which has only been collected twice before in the Phalaborwa area. It is known to occur in areas with extended droughts. It produces one extremely fragrant flower, which blooms for one night (possibly two), and produces one seed (rarely 3) when conditions are favourable (https://www.pacificbulbsociety.org/pbswiki/index.php/Crinum_minimum).
- At first, there was a significant emergence of various forb species, although the diversity of forbs emerging after the drought did not seem to be higher than the diversity of forbs in an average or wet year (to be tested with future datasets). Forb community changes after the drought were not only induced by the emergence of annual forbs, but also due to species-specific dominance shifts in the forb layer (Siebert et al., 2020). At some sites, geophytes emerged within a few days after the first rains (e.g. *Albuca seineri)* (Figure 52). These geophytic forbs are particularly important in tropical and sub-tropical grassy biomes as they contribute to important ecosystem functions and are known to contribute to a persistent bud-bank from which they regenerate as soon as conditions become favourable. Several geophytic forbs are toxic and may cause animal deaths after an extensive drought event since they are the first to emerge after a drought-release (because they have carbon and water storage organs that are kept below-ground as a drought-tolerant trait).
- Forbs seemed an important resource for some mammal species during and after the drought. Impalas were particularly attracted to 'greenness', which was induced by forbs in the post-drought landscape. Forbs are one of the most abundant food items in the diets of impalas and elephants during the wet season (see Siebert and Dreber, 2019 for more info). Even during the drought, several forb species were observed to have considerable browsing scars. The Forb Ecology Research group of the North West University is analysing DNA metabarcoding results of herbivore dung sampled during the drought (results pending).
- There was a drought-tolerant forb community in the granite landscape, which changed significantly in composition after the drought (Siebert et al., 2020). The drought-tolerant species can however not be associated by one specific 'guild' or forb functional group since their responses were very site-specific, probably due to their species-specific responses to soil conditions (Siebert and Dreber, 2019). Some of the more lignified (i.e. 'woody') forbs dominated considerably in certain areas (e.g. *Sida* and *Hibiscus* species) (Figure 51). They are all perennial forbs that were hardly seen during the drought, although they have the ability to resprout as soon as conditions become favourable.
- There was an expectation that the drought would help new grazing lawns to form and stay maintained. This did not happen as far as could be seen. Everything seemed like the same dust bowl until the rains came and what was once grazing lawn remained grazing lawn with no visible increases. It seemed as if the drought was not a catalyst for creation of grazing lawns (but see other comment where it was argued that in areas with less severe loss of herbaceous biomass, grazing lawns did seem to expand during the drought, and also the proliferation of hippo lawns in the rivers).

- It seemed as if there were differences in the "resilience" of the herbaceous layer to drought depending on the underlying geology – standing grass on the granitic derived soils seemed to "last" longer, whilst standing grass was observed to be more limited on basaltic derived soils. However, after the rains returned, it seemed as if there was an explosion of grass biomass observed on the basalts as opposed to a partial recovery on the granites. This can possibly be tested using Vegetation Condition Assessment (VCA) data.
- In contrast to woody plants, the grass layer was severely impacted in the Phalaborwa area, the Letaba Ranch area, Hoedspruit Wildlife Estate, and in Olifants West Nature Reserve. Many perennial tufts died, and others were severely reduced in size (Figure 54). Around the offices at the Phalaborwa gate, *Themeda triandra*, *Digitaria eriantha* and *Bothriocloa radicans* appeared to be the most severely affected, with many tufts of these dead by the end of the 2015/16 summer. By 2019, all the other perennial species had suffered mortality as well, most notably *Panicum maximum, Heteropogon contortus* and *Schmidtia pappophoroides*. Grazing contributed to the die-off, as almost all growth was grazed down short during the growing season (mainly by impala). Also, areas protected from grazing (just outside Phalaborwa Gate) showed far less die-off, with swards of *Panicum maximum* persisting throughout the drought. By 2016, a massive switch in grass composition had occurred with annual species now dominating, particularly *Brachiaria deflexa* (at Phalaborwa and Hoedspruit) and *Setaria pumila* (apparently limited to Hoedspruit area). These species were completely absent in the years of average rainfall that preceded the drought, although they were more common around 2008/09. They must have sprung up from a large seedbank, in response to more light reaching the soil (or perhaps higher soil temperatures). They were largely restricted to areas directly beneath tree and shrub canopies, with lots of bare soil and a sparse cover of *Aristida (congesta or adscensionis*) and *Tragus berteronianus*. North of Phalaborwa, these species also became the dominants, but were less dense and there was more bare ground.
- The grass layer was less impacted in the Orpen-SA Wildlife College area. While productivity declined, there was apparently much less death of tufts, and overall grass cover remained higher. *Panicum coloratum* seemed to be more common than before, and genuine grazing lawns seemed to increase in size (in areas where herbaceous layer was more severely affected by the drought, this did not seem to be the case – see earlier).
- In the Satara area, die-off of perennials and a massive reduction in standing biomass was observed, but there was a rapid recovery in 2017/18 when rainfall was slightly above average. This was primarily due to rapid colonization (presumably from seed) by *Urochloa mossambicensis*, and certain forbs.
- A long-term vegetation study on the Satara Experimental Burn Plots (EBPs) has collected data for a number of years before, during and after the drought. Some key observations from this study are:
    - Biomass
        - Near complete absence of biomass production (Annual Net Primary Productivity) during the drought (2015/16)
        - Recovery to 'normal' pre-drought levels in 2017, but forb biomass exceeded grass biomass – something not seen previously in the 12 years on the permanent vegetation plots being monitored.
        - An interaction with fire, with unburned control blocks being less dynamic in terms of biomass changes than either the annually or triennially burned blocks.
    - Dominance
        - In terms of cover (and biomass) dominance switched from grass to forb in the 1st year of drought recovery, but then reverted back to a grass-dominated system.
        - Perennial grass and forb species were lost during the drought, to be replaced by annual species.
        - In terms of the grass community, dominance by the unpalatable, fire tolerant climax species *Bothriochloa* was broken and replaced by relatively more palatable pioneer or subclimax *Urochloa* (Figures 55-56). This was most pronounced where herbivory was present, irrespective of fire treatment.
- During January/February 2017 alien vegetation monitoring plots were to be resurveyed along the Sabie River as part of an alien plant monitoring programme. It was not possible as there was no vegetation at the sites - not even any alien species.
- It would appear that throughout the last few years the aggressive alien invasive herbaceous species *Parthenium hysterophorus* has been doing well, and spreading steadily. *Parthenium* seems to prefer areas with low competing species abundance, so it might use the opportunity of bare ground, or even the natural disturbance from animals walking on and breaking the surface of the open ground – the drought could produce such conditions. However *Parthenium* does need moisture as well, so it would only have been able to take advantage of this in moist areas – riparian areas, seep lines (natural or for example, below dripping water tanks). It grows very quickly, so if there was even a small rainfall event it is likely that it would respond much quicker than native vegetation. There is some debate on whether herbivores did in fact browse on *Parthenium* during the drought, which was not previously considered

even a possibility (Figure 39). The dynamics of an invading species like *Parthenium* makes interpretation difficult as the species are in the range expansion phase.

- Grazing lawns (or hippo lawns) in the rivers were apparent during the drought and especially during low flow periods in the years after the drought. In November 2018, and at the end of a relatively dry and hot year, large parts of the Olifants river was covered by grazing lawns that stretched for kilometres (Figure 58). It is not clear whether the below average rainfall over the period, lower flows, and concentration of herbivores on the rivers, in combination with the availability of soil moisture in these riverbeds, were partly responsible for these grazing lawns forming. Although most noticeable in the Olifants river, they were also observed in other rivers, e.g. Letaba, Timbavati and Sand rivers. Many animals and diverse species were grazing on these lawns – they teemed with blue wildebeest, zebra, warthog, waterbuck, impala as well as grazing elephants. Although these grazing lawns often form in these rivers, they seemed particularly well developed in the years subsequent to the drought and when low flows continued.

Figure 46: Basaltic areas around Tshokwane exposing the red soils in the absence of an herbaceous layer (photo: Cathy Greaver).

Figure 47: View from Nkumbe look-out point illustrating the comment that it was a "grazer" rather than a "browser" drought (photo: Izak Smit).

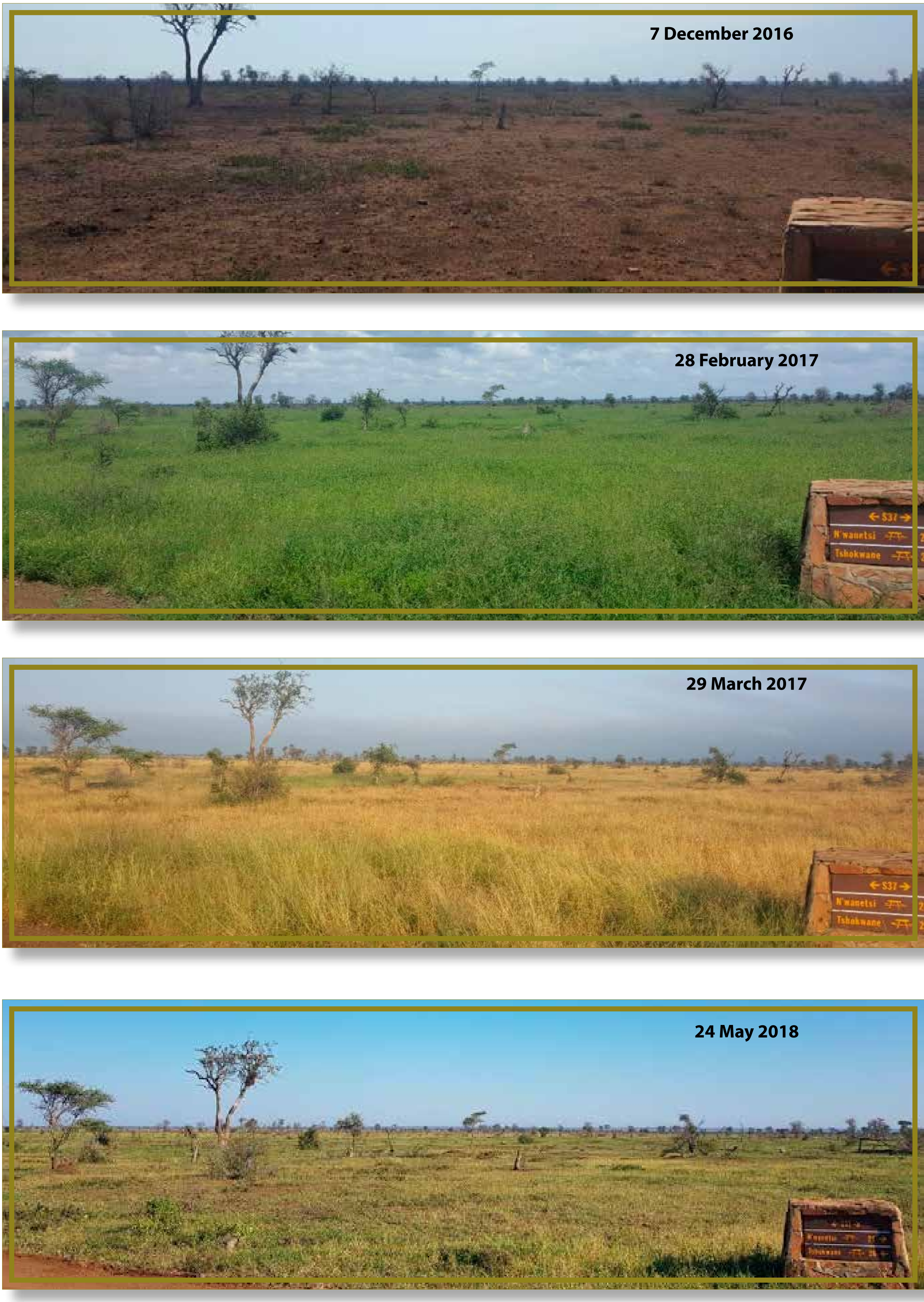


Figure 48: Sequence of photos showing drought and post drought responses in Nwanetsi section, which was at the epicentre of the drought (photos: Robert Bryden).

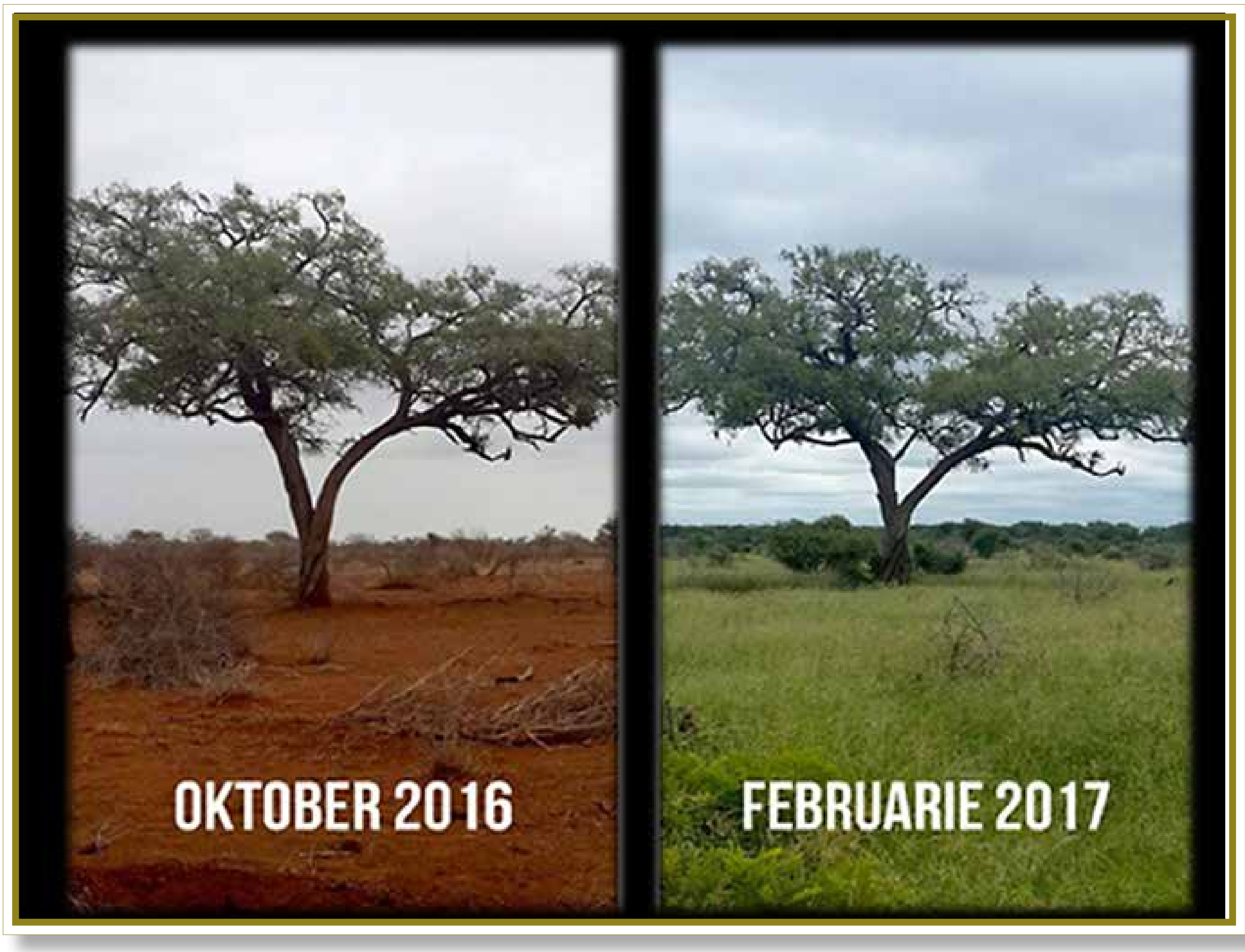


Figure 49: Recovery of herbaceous biomass after rains returned was remarkable (Photo: Guin Zambatis) – many respondents commented (Photo: Izak Smit) on the recovery of the herbaceous layer from the seedbank (photos: Carl Louwrens).

Figure 50: Forbs dominated the herbaceous layer after rainfall events during drought, as well as first growing season subsequent to drought (also notice the killed and/or topkilled *Dichrostachys cinerea*) (photo: Izak Smit).

Figure 51: Although lignified ("woody") forbs were almost absent during drought, they returned and dominated in certain patches after the drought, like *Sida*, *Hibiscus* and *Melhania* species shown above (photo: Francis Siebert).

Figure 52: Forb emergence after drought – often large stands of conspicuous forb and bulb species, e.g. *Albuca seineri* (bottom previous page; photo: Guin Zambatis), *Ammocharis coranica* (top; photo: Guin Zambatis), *Tribulus sp.* (bottom; photo: Izak Smit) and *Indigastrum parviflorum* (middle; photo: Kevin Wilcox), were noticed during drought after rainfall events, or in first wet season subsequent to drought.

Figure 53: *Crinum minimum* on the Phabeni road 0.78km NE of the S65 – only the third time ever observed in KNP. It is known to occur in areas with extended droughts. It produces one extremely fragrant flower, which blooms for one night (possibly two), and produces one seed (rarely three) when conditions are favourable.

Figure 54: Death of grass tufts was observed and the importance of post-drought recovery from seeds became apparent (Photo: Izak Smit).

Figure 55: Sequence showing (i) dead *Bothriochloa radicans* tufts during the drought (top), (ii) sprouting of primarily annual grasses with the return of the rain (bottom left), and (iii) dominance by *Urochloa mosambicensis* (bottom right) (Photos: Kevin Wilcox).

Figure 56: In 2014 this plot was 10% *Themeda triandra* and 90% *Bothriochloa radicans*. In 2017 the cover values were 85% *Indigastrum parviflorum*, 20% *Urochloa mosambicensis*, 6% *Themeda triandra* and <1% for each of 3 unidentified (too young) grass species (Photo: Sally Koerner).

Figure 57: Soil processes and soil contrasts became very apparent during drought in the absence of any notable herbaceous cover (photos: Izak Smit).

Figure 58: Grazing lawns (or hippo lawns) seemed to be more extensive after a couple of years of below average rainfall and the drought (photo taken from high water bridge over Olifants River looking eastwards) – many animals frequented these river-associated lawns and it appeared an important critical resource during the droughts and periods thereafter (photo: Izak Smit).

4.9.3. Vegetation outside KNP

- In the mesic-savanna rangelands around the road up to Mariepskop, no impacts of the drought on vegetation were evident, although cattle there did get skinny as well (but no deaths of these observed or heard of). Apparently no impacts were reported at all further upslope, in the plantations, forests and grasslands.

4.10. Management

- During the past drought there was a more relaxed, rather than anxious, feeling amongst managers and scientists due to a realization that drought is an essential process in savanna ecosystems, and that they "do more good than harm to such systems" (direct quote from manager). Managers and scientists alike have evolved in their approach towards droughts especially as there were still a number of them around that experienced the 1991/92 drought first-hand and had that historic knowledge. These colleagues with experience of previous droughts could calm colleagues who got anxious and wanted to open boreholes that were closed as part of the new KNP Water Provision Policy. This also led to better communication and engagement nationally with DEA when national drought action plans were drawn up and pro-active and balanced communication with the general public about the importance of such events in these semi-arid savanna ecosystems.
- KNP was much better prepared for this drought than previous ones according to a manager that experienced various droughts in the park. There was a proper monitoring program and research projects set up to monitor key aspects and learn key lessons. Certain boreholes were identified for special maintenance to provide water both for game and rest camps in emergency conditions.
- From previous droughts it was clear that there are not only ecosystem benefits that flow from droughts, but also socio-economic ones. The KNP Rivers Research Program (KNPRRP) and the Environmental Reserve embedded in the National Water Act that flowed from the KNP Rivers Research Programme (KNPRRP) are excellent examples. They also created (or forced) opportunities for cooperation with neighbours and relevant state departments, inter alia as different river forums, some of which still operate today. Another example is that during the recent drought there was an opportunity to share benefits in the form of very limited culled animals with neighbours. Also, droughts support the "bigger is better" notion for protected areas and supported the justification for the development of the Greater Limpopo Transfrontier Conservation Area (GLTFCA).
- Extremely high unnatural number of hippos in the Nwaswitsontso river from (man-made) Orpen dam downstream to the Harashu had an impact on the natural water in the Nwaswitsontso and Metsi system. Around 120 hippos were observed between the Orpen dam and Nwaswitsontso fountain – these hippo were believed to have mostly been a result of Shilolweni dam's hippos having had to move when the dam was breached some years ago, as well as Mazithi and Orpen dams' hippos as these man-made waterholes have dried up during the drought. As such the hippos dispersed into the smaller pockets of natural water as the man-made water sources were drying up (man-made dams were disconnected from critical groundwater resources – see section 4.6.). Their defecation in the water spoiled it as drinking water for other animals, which were dependent on this water as the drought intensified, with large numbers of buffalo dying around the Metsi fountain (likely due to starvation).
- After hippos were culled for two days at the Nwaswitsontso fountain, the remaining hippos dispersed (20 were left after 2 days of culling, and on the third day all of them had moved away). Same was observed at Orpen dam where there was large scale dispersal observed after a couple of days of culling.
- Large number of hippos moved to Bulweni Pans, Letaba section, during the drought (approximately 70 hippo between the 2 pans). It is most likely that the hippo moved to these pans from the Letaba river and Hlanganini dam, as the grazing along these water bodies was depleted and the grazing around Bulweni pans was much better as the pans were dry and had only shortly before received water – as such, these grazing areas were not reachable for hippo from the Letaba and Hlanganini dam before the pans filled up. Furthermore, there was a concern that there was an unnaturally high hippo population in the area due to population build ups in (man-made) Mingerhout and Hlanganini dams prior to the drought. Considering the above, there was a concern that the (unnaturally high) hippo numbers would pollute the water, and that the sediment base of these pans might be effected severely which may have an effect on the ecology of the pans in future years, as the pans will never be flushed clean as it happens to pools in river systems.
- In the Nwanedzi area a large number of over 100 hippo also moved into a small permanent spring in the Guweni spruit when the Gudzane Dam and WNLA dam about 20 km to the north dried up. When some kudu and hippo died from anthrax in the Gudzane dam area there was a concern that it could spread to this unnatural concentration of hippo in the Guweni spruit. The fear was that this could establish a new and permanent anthrax reservoir in an area very far from the "natural" anthrax reservoirs in the Pafuri area. About 10 hippo was culled at the Guweni spring over 2 days and the rest all then left the area.
- Some colleagues expressed the opinion that closure of artificial waterholes may possibly have lowered the mortality rates observed during the 2015/2016 drought and as such supported the management decision and action to close various artificial waterholes since the previous drought. One colleague however expressed dismay and anger towards the closure of waterholes in the light of droughts.
- Almost no veld fires were observed during the drought.

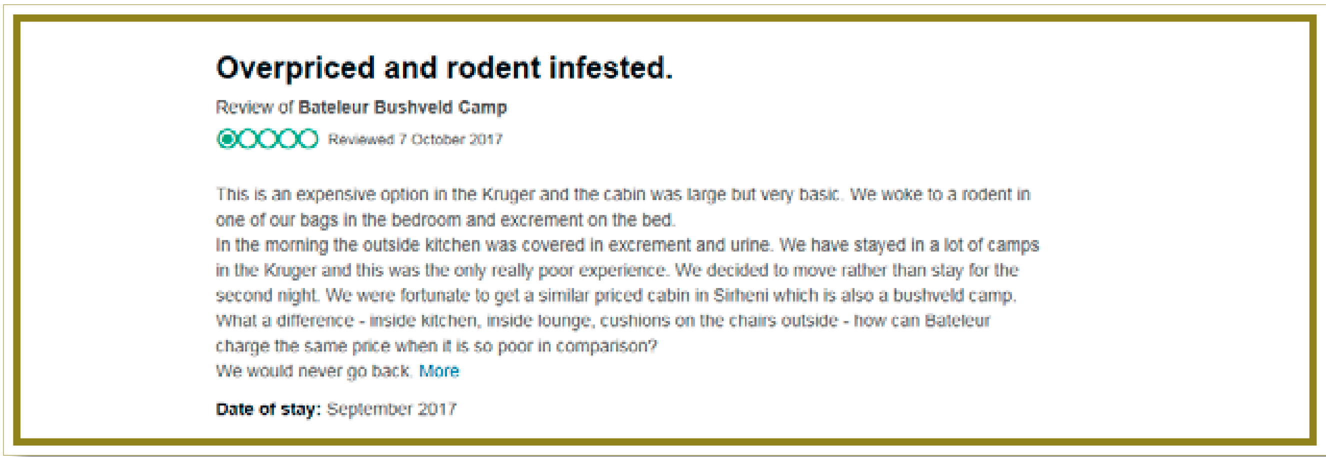
- There was a swap in fire risk linked to camps. Usually the fire risk is as a result of fires from outside the camp jumping into the camps. But during the drought there was a greater fire risk inside the camp. The herbaceous biomass in camps generally stays greener during normal years (it is not clear why this may be the case – possibly because it gets mowed from time to time and/or due to the lack of herbivory which selectively removes green vegetation and/or due to more shade from higher woody cover within camps). However, during the drought the herbaceous layer in the camps was extremely dry, and high biomass had accumulated over many years, and this posed a much greater fire risk in camps (barely any fuel biomass outside camps). As such, during the drought, management conducted more burning for fuel reduction within camps than outside camps.
- It was noticed that some (not all) colleagues continued to water their lawns as per normal during the drought when it was obvious that the rivers were in dire condition. The financial subsidy that staff receives for water (and electricity) may be a reason why some colleagues were seemingly indifferent to water shortages even after various awareness campaigns. Other staff were more water conscious during the drought.
- Many animals travelled to waterholes at night and waited in the morning for solar pumps to pump water – these pumps could not keep up. Also, animals were observed apparently waiting at water sources in anticipation of wind turning the windmill to pump water.
- A different kind of artificial waterhole was tested successfully (this was also done in the Levuvhu river during 1991/92 drought). This entailed a hole dug by a frontend loader in sandy rivers to expose water that occurs under the sand as part of the alluvial aquiver. This is a quick and easy waterhole without permanent impacts such as is caused by building dams and drilling boreholes. The one dug in the Nwaswitsontso river north of Tshokwane reliably retained water during the drought and is still there and has not closed up, even after several floods (Figure 59). This demonstrates the possibility of creating "emergency" water sources, should there be a need, by exposing sub-surface groundwater (see section 4.6. regarding the importance of groundwater resources during droughts).

Figure 59: This waterhole was created by a frontend loader excavating sand to expose groundwater in the Nwaswitsontso river (on H1-3 north of Tshokwane picnic site). The waterhole retained water throughout the drought and demonstrated the possibility of creating "emergency" waterholes in this manner at limited cost and with reduced long-term impact.

4.11. Tourism

- The rodent eruption in the summer after the drought (see section 4.3.3.) was also experienced in the tourist camps and led to various complaints by tourists (Figures 60-61). A Skukuza Duty Manager confirmed that there were many cases of tourists complaining about rodents in their huts, and requested to be moved to other huts during this post-drought period when the rodents experienced an eruption. A flyer explaining the situation was later developed to inform tourists as to the situation. The following is extracted from an e-mail that was sent to the Skukuza tourism colleagues from an international visitor (dated October 2017) – in some cases tourists demanded refunds, or asked to be moved to another camp/unit:

- *"We have stayed at your camp prior to this reservation with no complaints. Upon arrival we were confronted with cockroaches in the kitchen and when we tried to retire we had a snake in one of the bedrooms, we heard snakes going through the garden. In another room, there was a rodent (it resembled a rat with a similar tail but the head was a bit rounder than that of a rat). We have pictures as prove that it was in the bedroom sitting on top of the curtains. If an animal of that size could get in, there was also another possibility that this room would have snakes as well. Upon the price we paid for this accommodation we were expecting a safe environment. If you cannot offer that you should not be renting out these houses or it should specify 4 bedrooms, each with 2 single beds, air-conditioned and with dangerous occupants/pets. That way people can choose for themselves if they want to share their accommodations with snakes or not. We were definitely not happy with snakes, rodents and cockroaches and who knows what else in our rooms. I hope that you will compensate all the trouble we have had during that night. If you want me to send the pictures of the rodents and cockroaches as evidence, just let me know. We were not able to take pictures of the snakes. We were not looking for a confrontation during night time."*



Overpriced and rodent infested.

Review of **Bateleur Bushveld Camp**

Reviewed 7 October 2017

This is an expensive option in the Kruger and the cabin was large but very basic. We woke to a rodent in one of our bags in the bedroom and excrement on the bed.
In the morning the outside kitchen was covered in excrement and urine. We have stayed in a lot of camps in the Kruger and this was the only really poor experience. We decided to move rather than stay for the second night. We were fortunate to get a similar priced cabin in Sirheni which is also a bushveld camp. What a difference - inside kitchen, inside lounge, cushions on the chairs outside - how can Bateleur charge the same price when it is so poor in comparison?
We would never go back. More

Date of stay: September 2017

Figure 60: Tripadvisor review of Bateleur Bushveld camp by international visitors during the period when a rodent outbreak was experienced over large parts of KNP in the post drought period.

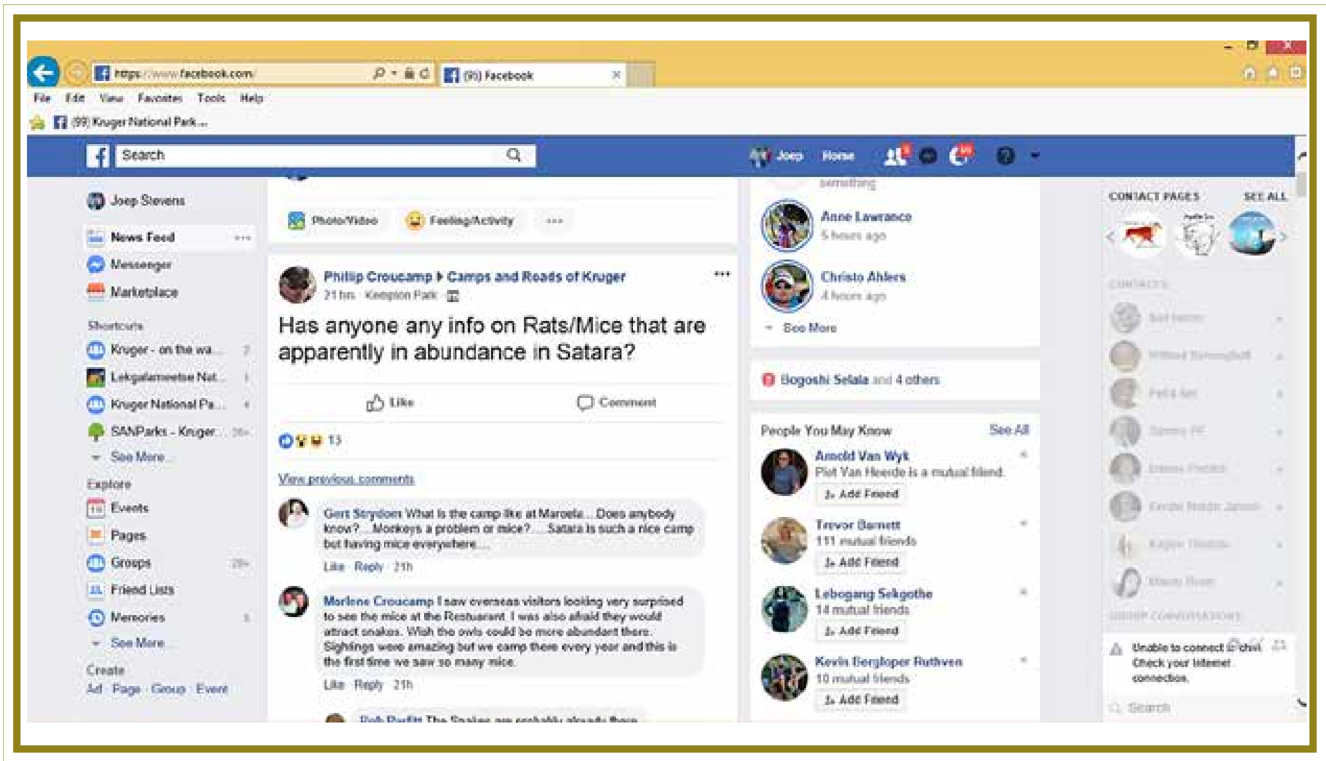


Figure 61: Facebook comments by tourists "sharing" experiences on rodent eruptions in camps, and speculating about concerns regarding snakes.

4.12. Comparing 2015/16 and previous droughts (1991/92 and 1982/83)

- Various colleagues suggested that the 2015/16 drought was patchier and spatially more variable than the 1991/92 drought. Furthermore, one colleague observed that for the central region the 2015/16 drought seemed more intense, but shorter when compared to the 1991/92 drought. This needs to be verified using historical climatic data.
- Many more hippos died during the 2015/16 drought than 1991/92 and 1982/83 droughts – for all other conspicuous mammal species, including buffalo, less individuals seemingly died.
- Usually kudu, impala, bushbuck and warthog are the first species to die during droughts, as was the case in 1991/92 drought. Based on oral accounts, dead animals (like impalas and bushbuck) were picked up on the side of the roads and on the Skukuza golf course in the mornings during the 1982/83 and 1991/92 drought – no such large scale mortalities were observed during the 2015/16 drought. The low impact of the 2015/16 drought on especially warthog (a facultative grazer that prefers green grass) is difficult to explain. During the 1991/92 drought the warthog population in KNP halved and desperate warthog were observed sticking their heads into car windows to beg for food and attempting to feed on elephant dung. For example, Tshokwane section ranger only observed one warthog to have seemingly died from drought in 2015/16, and no impala or kudu, and Houtboshrand section reported no kudu or warthog mortalities. Timbavati PNR also recorded only very isolated cases of mortalities of these species. It was hypothesized that this could possibly be ascribed to the fact that the drought was not as prolonged as the 1991/92 drought and that the trees still had some resources (i.e. browse) left. The critical periods of rainfall have also been mentioned as possibilities for the reduced mortalities and apparent lack of browsers dying (refer to section 4.1.) (Figure 62).
- Elephant, buffalo and rhino populations were higher in 2015/16 drought as compared to 1991/1992 drought – the rain that did fall in 2015/16 sustained the vegetation better to "carry" the animals through the drought.
- Natural water did not dry up "from the Letaba to the Luvuvhu rivers" as was stated for previous droughts. By surveying rivers during the most intense time of the drought it was clear that there was still adequate water available for game in most of the larger ephemeral rivers as pools, springs and in the form of elephant/rhino diggings where animals could find water to drink. Most springs continued to have water throughout the drought.
- During the 1991/92 drought a TLB dug for water at Crooks Corner, Pafuri – baboons, crocodiles, hippos, fish and birds died off, as well as umbrella thorns, fever trees and apple leaf trees.
- Rivers maintained their flow conditions much better during the 2015/16 drought than during the droughts of the 1980's and 1990's. During these years the once perennial rivers (all but the Sabie River) dried up completely for long periods, ravaging these ecosystems and causing the death of many large riparian trees. The Sabie River had less than 0.5 cumec of flow and one could jump over it in some places. The improved situation in the 2015/16 drought shows that the strategic decisions taken at that time to provide for rivers from dams (at that stage still to be built) in the upper catchments have worked. This important strategic redirection, i.e. to support the construction of large catchment dams in the upper catchments of KNP rivers rather than trying to provide adequate water from dams inside the Park, and the allocation of water in these dams (Nandoni in the Luvuvhu River, Inyaka in the Sabie River catchment, Kwena in the Crocodile River, etc.) for environmental purposes was crucial. Unfortunately the issue of water quality and trash washing down rivers has come in as new challenges.
- Large parts of KNP where boreholes have been closed over the past two decades still had good grass cover and the general feeling was (and hopefully the censuses will verify this) that rare antelope populations survived better during this drought than during previous droughts. It seems that even buffalo did not die in such large numbers as when Kruger had the wide-scale provision of artificial waterholes in the 1990's. However, other conditions (e.g. rainfall in the north) also differed between the droughts and need to be taken into account.
- The 1991/92 drought had a very severe anthrax outbreak associated with it, affecting a range of species. Very limited anthrax was observed during the 2015/16 drought, which may possibly be due to the fact that the northern part of the park, where anthrax is endemic, was slightly less affected by the drought due to better rainfall than the central and southern KNP.

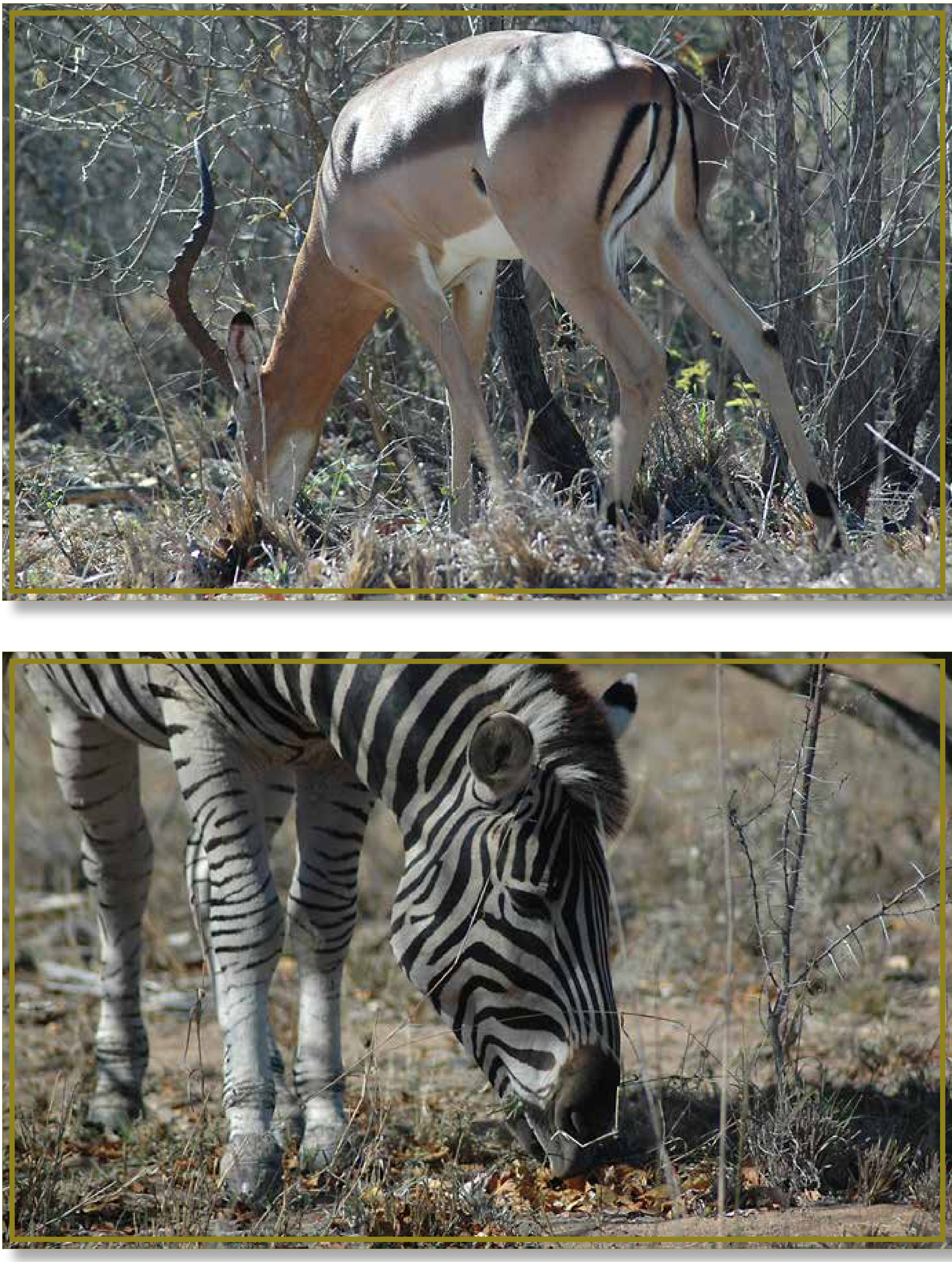


Fig. 62: Small rainfall events, and the temporal spacing between these events, are one of the reasons suggested for the generally lower mortality rates observed during the 2015/16 drought compared to 1981/82 and 1991/92 droughts. The photos above show impala and zebra picking out green forage during the height of the drought summer when a rainfall shower resulted in some green shoots emerging (photos: Izak Smit).

Conclusion

Impact of drought reverberated through the entire system from smallest to largest plants and animals. Some of the effects of the 2015/16 drought in the Kruger National Park were transient (e.g. various eruptions during and after the drought), whilst other effects were part of longer cycles (e.g. large scale dieback and mortality of *Dichrostachys cinerea* and hippos). Some effects were highly localised (trees of a particular species dying in a patch whilst others of the same species and same size classes in close proximity did not die), whereas other effects and distributional shifts played out over larger scales (e.g. species observed that were never or rarely recorded in the park before). It was also clear that animals adapt behaviourally (extending foraging time; foraging on resources not otherwise utilised; fragmenting herds) and spatially (movement to drought refugia; increased distances travelled between forage areas and water resources). The effects of the drought were species specific (some species advantaged, some disadvantaged and some seemingly unaffected), often patchy and interacting with other processes (herbivory and fire history) and the underlying abiotic template (geology). The first wet season after the drought was incredibly dynamic, with many post-drought eruptions across various taxa, which seemed to "normalise" within ~ 2 years. From a management perspective, various productivity and biodiversity advantages were observed from the drought (e.g. mortalities of bush encroaching *Dichrostachys cinerea* and replacement of dominant unpalatable *Bothriochloa radicans* grass with palatable *Urochloa mosambicensis*) and certain species are seemingly benefitting from the prevailing low rainfall cycle (e.g. blue wildebeest, black-backed jackal). The invertebrates, and the food web associated with them, were heavily affected with various crashes and eruptions associated with a range of invertebrate taxonomic groups. Reptiles, especially chameleons and snakes, were also seemingly heavily affected and are slow to recover to pre-drought densities. Considering the assessment presented here and observing the photos of the extreme conditions experienced during the drought, as well as the post-drought responses, highlights the resilience of savanna systems to cope with, recover from and reorganise as a result of these extreme events. It also suggests that some species may have evolved to exploit conditions that are most common during or immediately post-drought (the notion of "drought specialists").

Memory fades fast and depending on when the next severe drought is experienced, many of the 2015/16 manager and scientist generation may not be around (the dwindling generation that experienced the 1991/92 drought were critical in providing perspective and reducing anxiety during the 2015/16 drought). We found this project of collating drought related observations across many colleagues with many different interests and perspectives useful as it allowed some collective reflection, co-learning and sharing between scientists, managers, rangers and guides. We encourage further qualitative studies during future droughts to document observations and archive photos in order to increase the learning opportunities from these events and create a more holistic view of the many facets associated with droughts.

Photo: Laurence Kruger"

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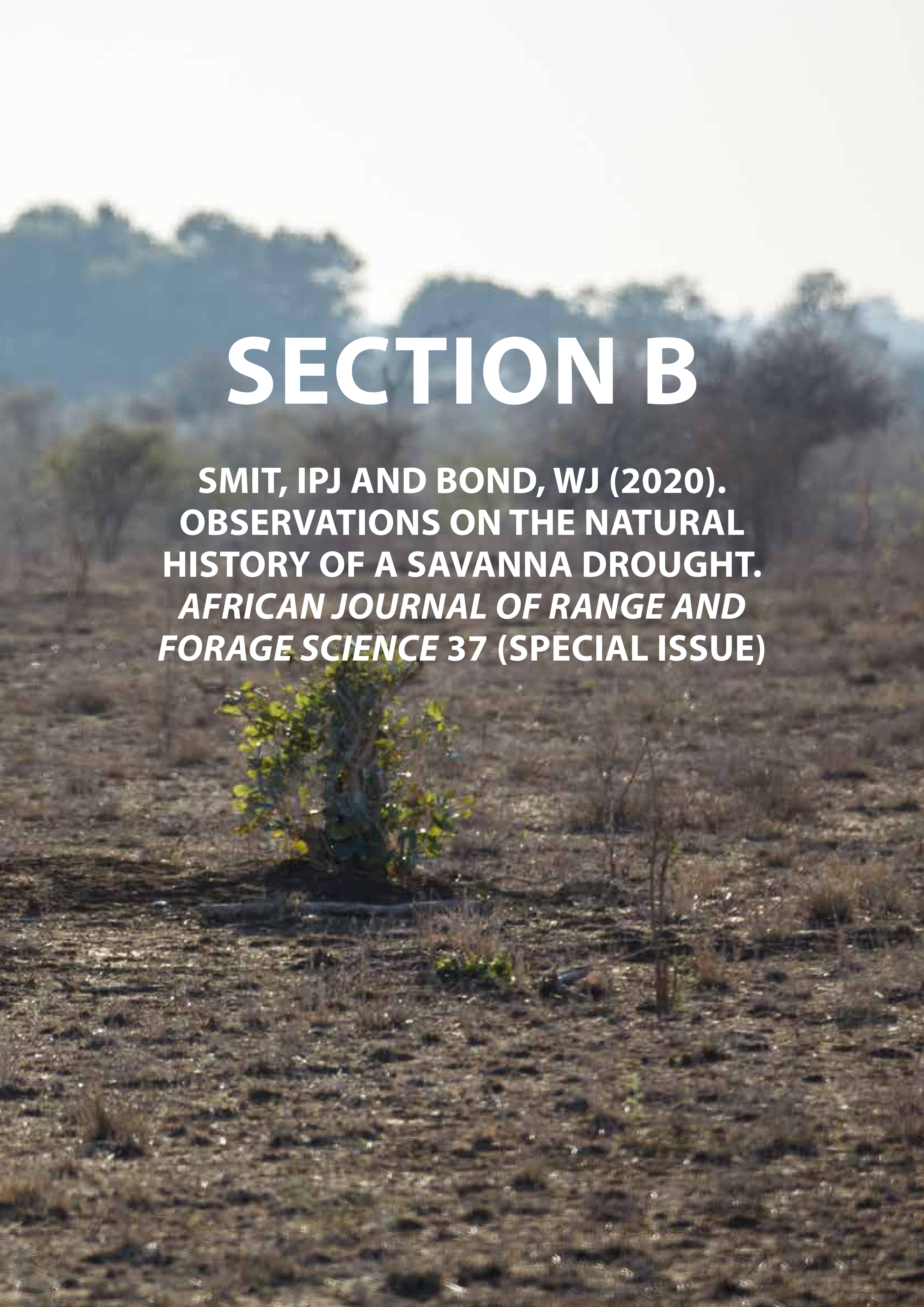
Photo: Laurence Kruger”



SECTION B

SMIT, IPJ AND BOND, WJ (2020). OBSERVATIONS ON THE NATURAL HISTORY OF A SAVANNA DROUGHT. *AFRICAN JOURNAL OF RANGE AND FORAGE SCIENCE* 37 (SPECIAL ISSUE)

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Observations on the natural history of a savanna drought

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Drought studies are often opportunistic and post hoc, where a drought fortuitously occurs during a research project that was not specifically designed to study the drought, but where researchers capitalised on the opportunity. These studies often lack focus on formulating and studying 'drought specific' research questions. By learning from observations during droughts, research gaps can be identified and drought specific questions can be formulated to be tested during future droughts. Therefore, in order to get a more holistic view of the ecology of drought, and in order to assist in formulating drought-related questions and/or hypotheses and identifying research gaps, we collected and collated observations and reflections from >50 persons who have lived and/or worked extensively in the Kruger National Park (KNP) and surrounding areas during the 2015/2016 drought. Many ecological lessons, interesting ideas, valuable insights and truly remarkable natural history observations were harnessed from these observations. We summarise them here to help prepare scientists in framing ideas on the functioning and role of droughts, and in designing research in anticipation of future droughts. These observations are not only valuable for scientists, but also for management. We reflect on lessons learned from previous droughts that led to changed management approaches that made the system more resilient during the recent drought. Although studies that focus on specific aspects of droughts are critical to enhance our understanding of droughts, narrative papers like this that cover many scales, taxa and processes can contribute to a broader synthesis and integration.

Keywords: climate change, drought research gaps, Kruger National Park, observational studies, savanna drought, resilience

Supplementary material: available online at https://doi.org/10.2989/10220119.2020.1723695

Introduction

Considering the importance of droughts as large infrequent disturbances, and the prediction that the frequency and intensity of droughts will increase in future (IPCC 2013), studies focusing on their ecological effects are surprisingly rare. One of the reasons for this may be that it is hard to predict when a drought will occur, which means that droughts often catch scientists by surprise, with funding timelines and student recruitment processes also not flexible enough to capitalise on these learning opportunities (Vetter 2013). During the 2015/2016 drought in the Kruger National Park (KNP), South African National Parks (SANParks; managing authority of KNP) specified that it would give special priority for registering drought related research projects (see Figure 1 for intensity and spatial variability of this drought). There was a surprising lack of reaction to this invitation, with scientists, indicating some of the reasons outlined above for their lack of response. Another reason for this paucity in drought studies is that it is not possible to do 'manipulative' drought studies, unlike fire (i.e. fire plots/treatments) (e.g. van Wilgen et al. 2007; Veenendaal et al. 2018) and herbivory (i.e. herbivore exclosures) (e.g. Asner et al. 2009; Wigley et al. 2014). The best attempt at simulating droughts is by manipulating rainfall amounts and intensity by making use of rainfall exclosures (February et al. 2013), yet these experimental setups cannot simulate large-scale drought effects (e.g. changes in mammal and insect herbivory, extreme maximum temperatures). As a result, drought studies are often opportunistic and post-hoc, where the drought just fortuitously happens to occur during a research or monitoring project that was not specifically designed to study the drought, but where the researchers capitalised on the opportunity presented (e.g. Breshears et al. 2009).

A number of studies reported in this special issue were not specifically designed to analyse drought effects and many facets of drought remain poorly studied. In a recent review of drought effects on tropical savanna vegetation, Sankaran (2019) acknowledged the value of observational studies when studying droughts, making use of such studies to compliment experimental studies manipulating plant water availability under controlled conditions. To try to give a more holistic view of the ecology of drought, we collected and collated observations and reflections from persons who have lived and/or worked extensively in the

KNP and surrounding areas during the 2015/2016 drought. Many ecological lessons, interesting ideas, valuable insights and truly remarkable natural history observations can be harnessed from these informal observations. We summarise them here to help prepare scientists in framing ideas on the functioning and role of droughts, and in designing research in anticipation of future droughts. Furthermore, these observations are not only meant to be valuable for scientists, but also for management. Lessons learned from previous droughts led to changed management approaches that have been interpreted as making the system more resilient during the recent drought (Venter et al. 2008).

Materials and methods

Data were collected by requesting colleagues that lived and/or worked in the KNP and surrounding areas to provide feedback on their observations and experiences during the 2015/2016 drought. Colleagues were individually emailed (or emailed in small groups of closely associated colleagues) and requested to reflect on the drought. The reflection was left open ended, but four 'prompting' questions were used as a way of stimulating feedback:

- What did you see during the drought that was exceptional or unusual?
- Any interesting observations or perspectives on the post-drought period (i.e. what interesting things did you observe after the drought that you think were triggered as a result of the drought?).
- What did you see or perceive during the drought that was similar or different from the previous drought in 1991/1992 (for those that experienced previous droughts in the park)?
- What were the biggest 'surprises' for you during this drought and the period thereafter?

Feedback and/or photos were received from more than 50 respondents that are involved in various capacities within the park (close to 70 potential contributors, mostly KNP staff, were directly requested to provide feedback and some of them forwarded requests to additional potential respondents) (Table 1). Most respondents provided feedback by email, whereas a small proportion provided input through telephonic conversations and two sent voice notes. Information was also extracted from observations during the drought submitted to the Curator of the Skukuza museum, located at the Headquarters of the KNP, as well as ranger diaries.

The collated information was sorted and analysed into three levels of increasing synthesis and abstraction:

- Level 1 – Verbatim narratives: Raw narratives as provided by respondents
- Level 2 – Cleaned and structured summary of observations: Raw narratives from Level 1 above were cleaned, thematically combined and summarised within a sensible layout/structure, but still retaining a high level of detail (e.g. locational information). This information is contained in Smit and Bond (2020) and is available from the authors or Skukuza Reference Collection.
- Level 3 – Key generalisations: Key generalisations were extracted from Level 2 above. These generalisations focused on identifying consistent and/or pertinent observations. This level of abstraction included some interpretation, integration and synthesis from Level 2 observations and is the content contained within this manuscript.

This study collates literally thousands of hours of field observations, often from experienced conservationists, conservation managers, rangers, natural history scholars and scientists, many with particular expertise and interests. This wealth of information is hard to capture in any predesigned study. However these natural history observations allow for an interdisciplinary, holistic and systemic view of the drought that compliments formal research studies.

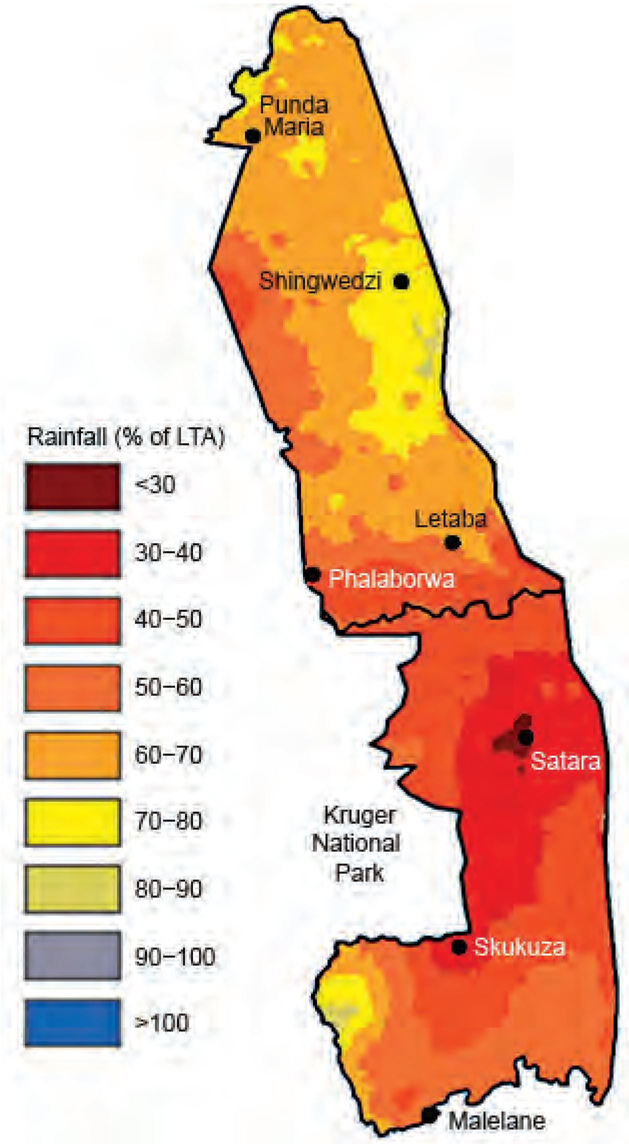

Figure 1: Rainfall during 2015/2016 as percentage of long-term average (%LTA; 1978/1979–2017/2018), indicating that the Kruger National Park (KNP) experienced far below average rainfall conditions, especially in the central parts of the park where rainfall stations recorded the lowest annual rainfall on records (Figure redrawn with permission from Malherbe et al. 2020)

Table 1: Feedback on the drought was received from 51 people across a range of involvement and experience of the Kruger National Park (KNP)

KNP employees (living in the park)	
Rangers	11
KNP scientists	9
Biotechnicians	5
Conservation managers	5
Technical services	1
Tourism	1
Veterinary wildlife services	1
Other	1
Non-KNP staff (not living in park unless otherwise indicated)	
External scientists	12
State Veterinarians (living in park)	2
Freelance trails ranger	1
Conservation manager of protected area adjoining KNP	1
Visitors to park (general public)	1

The observations are prone to various challenges:

1. Observer bias, as a result of preconceived perceptions (e.g. observation that lions spend more time around waterholes during drought — was this really the case or was this better noticed based on a preconceived perception that this would be expected?)
2. Attribution, e.g. can tuberculosis that was observed in KNP rhino for the first time be attributed to the drought or was it coincidental?
3. Improved visibility during drought, as a result of lower vegetation cover can result in observation biases (e.g. observing certain bird species, because of reduced cover, rather than as a result of increased abundance; carcasses were more exposed and hence more noticeable).

These challenges are by no means unique to qualitative studies. We addressed them, to some extent, through triangulation between various observations through our Level 3 abstraction process described above, but we do acknowledge the caveats.

Some of the observations noted in this paper are based on scientific studies conducted in the park and have already been published or are in the process of being published (some as part of this Special Issue). The scientists involved kindly offered some 'headline' statements from their studies where their observations were informed also by data collection and analyses, and more detail can be obtained from the relevant references. Some of the observations or perceptions can possibly also be tested using existing data, e.g. the Veld (Rangeland) Condition Assessment (VCA) data could be used to test the observation that herbaceous biomass was less resilient on basaltic soils than on granitic soils. Similarly, demographic surveys can test calving responses of megaherbivores. Such 'tests' of the validity of the observations made in this assessment are beyond the scope of this manuscript. Instead we trust that this compilation will stimulate interest in perceived effects of drought that can help frame hypotheses and tests using existing data or guide formal observations and data collection in future droughts.

Results and discussion

This section summarises key generalisations or pertinent observations regarding the drought, with some level of integration and synthesis, which emerged from the more detailed field observations reported by respondents (Smit and Bond 2020).

Highly dynamic herbaceous layer

Herbaceous biomass was severely reduced during the drought (Staver et al. 2019; Peel and Smit 2020; Wigley-Coetsee and Staver 2020), with many perennial grass tussocks dying. This mortality of perennial grasses was seemingly more common in areas with herbivore presence. Once the rains returned, forbs and annuals were the first herbaceous functional groups to return to the bare areas (Siebert et al. 2020), resulting in a changed species composition in the herbaceous sward. The fast and significant recovery of bare areas from the seedbank was noted as exceptional by various respondents. In some cases the grass layer that returned after the drought was more palatable than the grass layer that persisted for years before the drought (Wigley-Coetsee and Staver 2020). This change in composition was seemingly unaffected by various herbivory and fire regimes prior to the drought, suggesting that drought may be a particularly important disturbance process in savannas, driving longer-term dynamics in the herbaceous layer (Thompson 2017).

Abiotic template and disturbance regimes give rise to heterogeneous drought effects

The drought effect seemed heterogeneous, even for similar rainfall, as a result of drought interacting with the underlying template (geology, soils and catenal position) and disturbance regimes (i.e. fire history and herbivory) (Sankaran 2019; Swemmer 2020). Herbaceous biomass loss seemed more pronounced and post-drought recovery more exuberant on basalts, compared with granites. Similarly, tree mortality seemed higher on the basalts than on the soils of granitic origin (Swemmer 2020). In addition, termite activity seemed more pronounced on the nutrient rich basaltic soils, as opposed to the more nutrient poor granitic soils, similar to what was observed during previous droughts in the park (Braack 1995).

Disturbance and disturbance history (grazing and fire) interacted with drought. Perennial grass survival seemed reduced in areas where grazing occurred, as opposed to areas where grazing was excluded. Similarly, herbaceous standing crop seemed more reduced on areas that burnt prior to the drought, as opposed to unburnt areas.

Species-specific responses

Not all taxonomic groups or species within taxonomic groups were equally susceptible to the drought. Extensive large mammal mortalities were limited to the bulk grazers, buffalo (*Syncerus caffer*) and hippo (*Hippopotamus amphibius*) (Figure 2) (Duncan et al. 2012; Abrahams et al. 2019). Body condition of another bulk grazer, white rhino (*Ceratotherium simum*), was poor in the epicentre of the drought (i.e. central KNP), and some mortalities of older animals, as a result of starvation, were recorded (Ferreira

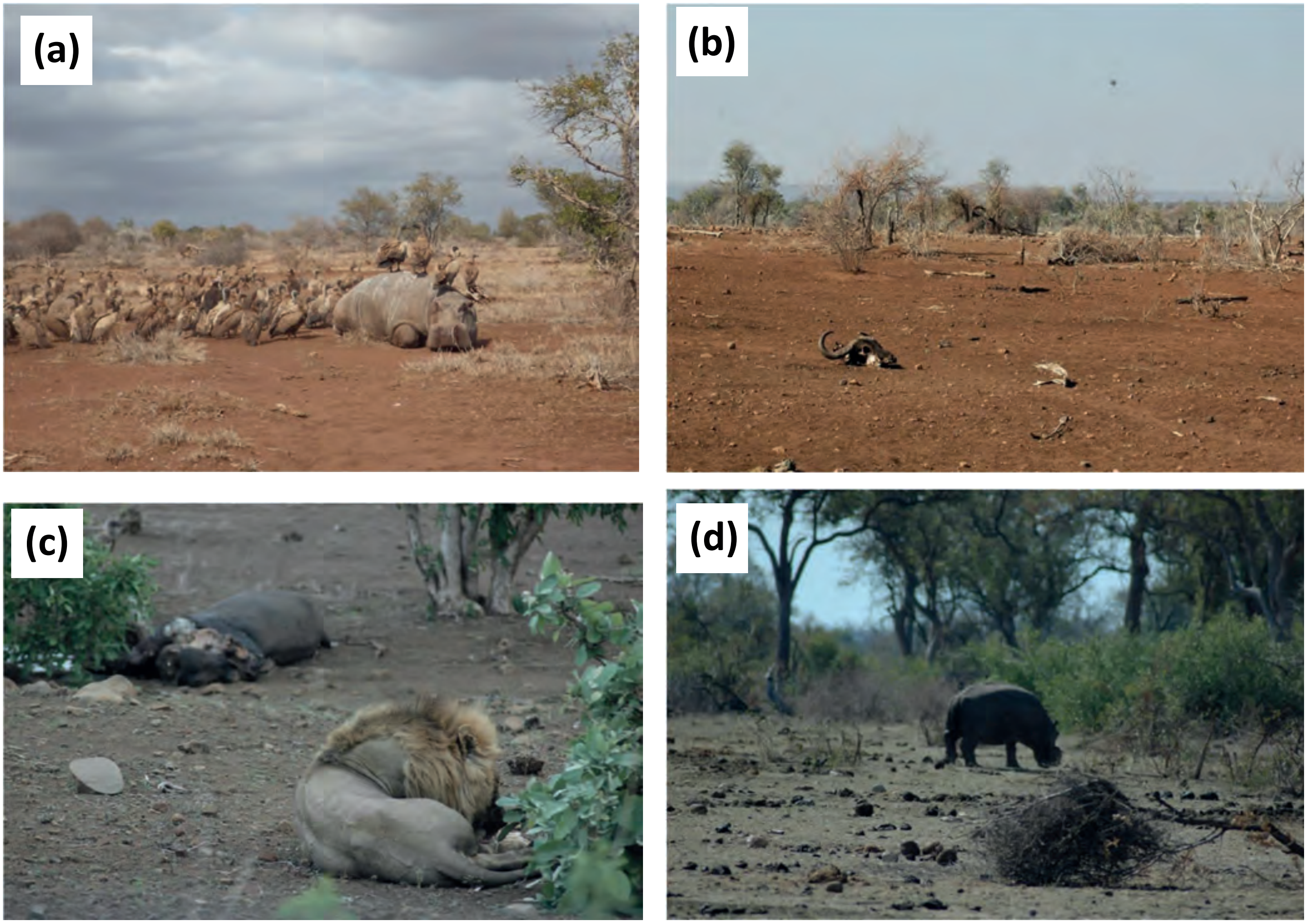

Figure 2: Megagrazers were the mammals where the largest mortality rates were observed in the Kruger National Park. Mortality was as a result of increased predation of emaciated animals and starvation, with hippos found far distances from water in the heat of the day in search of forage. (a) a hippo that died of starvation far from water in search of food; (b) large areas with limited forage lead to starvation induced mortality; (c) lions were seen feeding (and possibly predating) on hippo carcasses; (d) an emaciated hippo in search of grazing during the middle of the day (Photos a: Danie Pienaar; b–d: Izak Smit)

et al. 2019). Some respondents expressed surprise at the very limited extent of mortalities observed for elephants (*Loxodonta africana*), because large-scale mortality has been observed in other protected areas in Africa during droughts e.g. Tsavo, Kenya (Corfield 1973) and Hwange, Zimbabwe (Wato et al. 2016). At least two cases of elephant calves seemingly predated on by lions were reported by a ranger in central KNP.

The drought was aptly described as a 'grazing drought' by a respondent, because of the lack of mortalities observed for browsers and mixed feeders, and the apparent adequate surface water resources that remained during the entire drought period (refer to "*Groundwater creating drought refugia and affording buffering capacity*"). Interestingly, though, smaller facultative grazers like warthog (*Phacochoerus africanus*) were not affected, unlike in previous droughts (see "*Temporal distribution of rainfall is critical*" and "*Expect surprises - no two droughts are exactly the same*", where temporal distribution of rainfall is discussed as a possible explanation). This is consistent with Dunham (1994) who observed that larger grazers like buffalo die before smaller grazers like warthog during droughts — one can speculate whether the 2015/2016 drought was not as protracted for grazers as earlier droughts (see Malherbe et al. 2020). In addition, warthog frequently dig out belowground plant organs that may also have partly buffered them from the drought effects (although this does not explain their drought susceptibility observed during earlier droughts).

Some species known to prefer open habitats and arid environments (blue wildebeest [*Connochaetes taurinus*] and black-backed jackal [*Canis mesomelas*]) have been observed to increase in recent years and/or are seen in bigger groups/herds, even before the drought episode, which may potentially be in response to the prevailing below-average rainfall cycle. Considering rainfall cycles, Mills et al. (1995) found that blue wildebeest and zebra (*Equus quagga burchellii*) population densities were inversely related to rainfall, whereas buffalo and waterbuck (*Kobus ellipsiprymnus*) densities were positively related to rainfall, most likely as a result of prey switching by lions.

Similarly to the large mammals described above, selective mortalities were also observed for woody vegetation

(Swemmer 2020). Sickle bush (*Dichrostachys cinerea*) (Figure 3) and tamboti (*Spirostachys africana*) seemingly experienced wide and relatively large-scale die-offs. Sickle bush is widely considered a bush encroacher species in Southern African savannas, and is relatively resilient to herbivory and even fire (e.g. Wakeling and Bond 2007). Droughts may be an important disturbance mechanism to manage the density and distribution of certain bush encroachment species (Roques et al. 2001; Case et al. 2020). Sickle bush, one of the worst bush encroachment species in southern Africa, seems to be particularly sensitive to droughts and was also one of the species where wide-scale mortality was observed during previous droughts in KNP (Viljoen 1995a). Mortality of other species like silver cluster-leaf (*Terminalia sericea*), Delagoa thorn (*Acacia welwitchii*), velvet corkwood (*Commiphora mollis*), weeping wattle (*Peltophorum africanum*), magic guarri (*Euclea divinorum*) and Natal mahogany (*Trichilia emetica*) were less conspicuous, but died off in certain areas or patches. Although not widely reported, some large individuals of knob thorn (*Acacia nigrescens*) and occasionally mopane (*Colophospermum mopane*) and leadwood (*Combretum imberbe*) also died off in specific localities. An interesting observation was that some, especially large, trees only died about three years after the drought. Limited information is available on the mechanism underlying tree mortality, which can include any one or a combination of factors like hydraulic physiological stress/deterioration, dropping of groundwater levels ("*Groundwater creating drought refugia and affording buffering capacity*"), increased herbivory impact (e.g. increased utilization of bark and/or roots during dry periods by elephants, termites and other browsers), or possibly even increased susceptibility to disease (e.g. fungal attack). Understanding the mechanism of tree mortality rather than describing the areas and species affected by drought may be an important future research focus, because this will enable some predictive ability concerning traits associated with drought vulnerability.

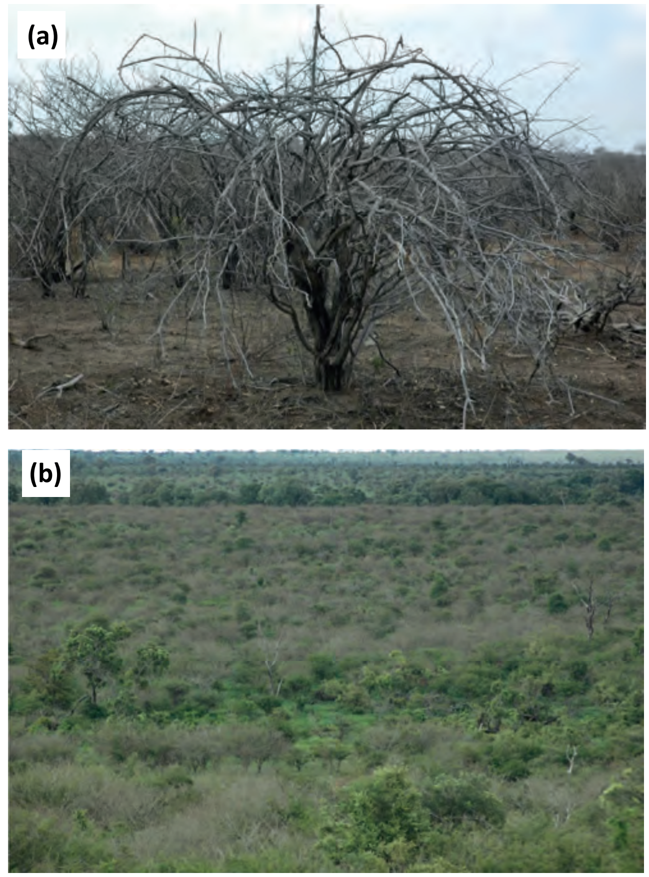

Figure 3: *Dichrostachys cinerea* experienced large-scale mortalities and top-kill over a wide extend, both in the 1991/1992 and 2015/2016 drought. *Dichrostachys cinerea* is known as a bush encroachment species and drought seems to be an important disturbance mechanism managing the density and distribution of a species that seems largely resilient to herbivory and dry season fires. (a) Many *D. cinerea* skeletons were seen after the drought; (b) Topkill and mortality of *D. cinerea* over large landscapes were noticeable in the wet season after the drought (Photos: Izak Smit)

Large-scale movement of species

Various large-scale movements of mobile species were observed and various species were recorded outside their normal distributional ranges. This was especially noticeable for birds. Some bird species were recorded in KNP that do not normally occur here or are rarely observed (e.g. Marico Flycatcher (*Bradornis mariquensis*), Red-capped Lark (*Calandrella cinerea*), Narina Trogon (*Apaloderma narina*), Pink-backed Pelicans (*Pelecanus rufescens*), European Wheatear (*Oenanthe oenanthe*), Lesser Jacana (*Microparra capensis*), Mountain Wagtail (*Motacilla clara*), Blue-mantled Crested Flycatcher (*Trochocercus cyanomelas*), whereas some usually common species seemed less common (e.g. fewer water birds, Wattled Starlings (*Creatophora cinerea*), large migratory eagles and migratory storks, e.g. White Stork [*Ciconia ciconia*]).

The first ever known record of freshwater jellyfish (possibly *Limnocnida tanganjicae*) was recorded in KNP during October 2016 at the height of the drought. These species are better known to occur farther north in Africa, with a few isolated cases recorded in South Africa in the past (Oldewage and Shafir 1991).

Movement to and increased utilisation of drought 'refugia'

Various mobile species moved to areas, or increasingly utilised areas, where conditions were more favourable, supporting the notion that certain areas can act as drought refugia. Notable refugia areas in the park for a range of taxa included rivers, permanent and/or ephemeral surface water sources, regions that experienced higher rainfall relative to other areas, and even the Skukuza staff village with its watered gardens and higher woody cover.

At a regional level, population responses of especially buffalo, but also hippo, elephant and white rhino reflected regional rainfall distribution (with the north and south-west of the park receiving considerably more rainfall than the central and south eastern areas during the 2015/2016 drought) (Figure 1; Malherbe et al. 2020). These areas seemed to have acted as drought refugia, either through lack of mortality (of resident animals), differential birth rates and/or movement into these areas (Augustine 2010; Abraham et al. 2019; Staver et al. 2019; Smit et al. 2020).

At a local scale, buffalo and elephant densities seemed to have increased around rivers during the drought. Hippos moved into springs and seasonal pans where they normally do not occur (or occur in low densities) when grazing conditions around these sources were more favourable than around their regular locations, or when their regular water sources (often artificially constructed dams) dried up. It became apparent again that artificially constructed dams were problematic, because they often hosted high densities of hippo that needed to disperse (or die) when these water sources that are disconnected from groundwater, dried up during the drought ("*Groundwater creating drought refugia and affording buffering capacity*"). Small groundwater-linked pools with very high densities of hippos were a common sight.

The Skukuza staff village with its denser woody vegetation, and watered gardens, also acted as a drought refuge, albeit on a smaller scale, and was heavily utilised by mesobrowsers, especially impala (*Aepyceros melampus*), bushbuck (*Tragelaphus scriptus*), nyala (*Tragelaphus angasii*) and kudu (*Tragelaphus strepsiceros*). Hippos and elephants also damaged fences and gates almost on a daily basis in order to raid gardens. The average monthly fence and gate breakages that were reported in the Skukuza staff village for repair during the drought increased four-fold (37.4 breakages/month between January and August 2016 versus background rate of 8.6 breakages per month across 59 non-drought months). The biggest increase in fence breakages during the drought was attributed to hippos (184 breakages in eight drought months, as opposed to 38 breakages across 59 non-drought months). These estimates are considered conservative, because some staff stopped reporting fence breakages. This is in agreement with other studies that showed that wild animals utilise areas with higher human densities more and become more dependent on urban landscapes during poor food years, typically droughts. Baruch-Mordo et al. (2014) noted the temporal 'urbanisation' of bears during years with poor food availability, whereas Waite et al. (2007) noted how a city became a sanctuary during droughts for Hanuman langurs (*Semnopithecus* sp.) where humans fed the monkeys throughout the drought period for religious reasons.

On days of extreme heat, insects also swarmed in unusual densities into shaded undergrowth in Skukuza gardens and the noise and activity levels were exceptional on days of extreme temperature.

Drought impact on lesser-studied taxa

Various lesser-studied taxonomic groups (and in some cases specific species within these taxonomic groups) have been severely influenced by the drought and may still be in recovery phase even three years after the drought. The reduction, described by some as a total 'collapse', in invertebrate numbers was very apparent, widely observed and noted by numerous respondents. This reduction in abundance and biomass was noted for insects in general, some specific insect groups (e.g. dung beetles, moths, stick insects), but also for other invertebrate groups (e.g. orb spiders and millipedes). One respondent visiting the same area almost on a weekly basis indicated how his clothes were usually covered in spider webs after fieldwork, whereas in the past summer (already three-years post-drought) he observed possibly only four orb spiders in total. This reduction in invertebrate biomass may have cascading effects on various other taxonomic groups. For example, a turnover in dominance in insectivorous bird species was also noted during systematic bird surveys. Linked to reduced invertebrate biomass, tourists also reported emaciated and unusually tame/disorientated civets, (*Civettictis civetta*), during the day in tourist camps and on tourist roads. This behaviour can possibly be linked to the lack of millipedes, an important food resource of civets, rather than disease or habituation. The post-drought recovery dynamics remains unclear.

Reptile abundance (i.e. snakes, tortoises and chameleons) also seemingly decreased. Very few studies have been done on the effect of droughts on reptile survival. Recovery of some reptile taxa has been slow since the 2015/2016 drought in KNP, with snakes only starting to show signs of recovery three years after the drought and chameleons still seemingly slow to recover. Sperry and Weatherhead (2008) observed the deterioration of snake condition and increased mortality during droughts, most likely the result of lack of food (i.e. rodents), and lack of cover, leading to increased predation. Pomara et al. (2014) suggest that droughts can cause local extirpations of dispersal-limited snake species. Literature on other reptile taxa seemed very limited.

During the next drought the population responses of invertebrates, taxonomic groups dependent on invertebrates, and reptiles, as well as their subsequent recovery, need to be more closely monitored. Worldwide there is concern on the apparent decline in insect diversity and biomass, even in protected areas, and the role of climate change, and drought episodes, also needs to be considered (Hallmann et al. 2017; Rhodes 2019). Janzen and Hallwachs (2019) reflect on the general decline in insects in the tropics, and also highlight the role that *El Niño* associated droughts can play in these collapses. We postulate that the predominant focus on the more charismatic or conspicuous groups (like large mammals and vegetation; Smit et al. 2020, as a point in case) may result in crashes of entire food webs going largely unnoticed, as was seemingly the case for the insect collapse over recent years.

Drought and post-drought eruptions

Various outbreaks/eruptions occurred during the drought, but especially in the first (and in some cases second) year after the drought, these eruptions were observed across various taxonomic groups, most notably rodents, birds, insects and forbs.

One of the most notable post-drought eruptions, was the wide-scale explosion of rodents in southern and central KNP. Rodent outbreaks after droughts are a well-known phenomenon (Saunders and Giles 1977). Sherman trapping success in the years before the drought was approximately 40%, which dropped to ~5% during drought and then erupted to ~80% trapping success for the first two winters after the drought. Normal trapping success of approximately 10–30% was again recorded in the third winter after the drought. The rodent eruption was not only noted by these trapping studies, but was obvious to the casual observer when driving at night with rodents continually crossing roads and many tourist (and staff) complaints of 'rodent infested' accommodation. One author had damage to his vehicle (vacuum brake pipe and air conditioner) caused by rodents. This outbreak of rodents co-occurred with increasing observations of owls sitting on roads at night, specifically spotted eagle owls (*Bubo africanus*) and grass owls (*Tyto capensis*) were mentioned, but a general lack of observations of snakes (see "*Drought impact on lesser-studied taxa*").

The most conspicuous eruption linked to the 2015/2016 drought in the KNP was the massive outbreak of red-billed queleas (*Quelea quelea*) in the summer of 2017. The outbreak was larger than any previous one in living memory of the park and amounted to hundreds of thousands of individuals (Figure 4 and Supplementary Video), often with many raptors perching in areas where they swarmed.

Figure 4: Various eruptions were experienced in the first wet season after the drought. Red-billed queleas (also see online video as part of supplementary material), rodents and some insect species (like moths and stinkbugs) were the most conspicuous. Raptors were often plentiful near the quelea swarms, and increased observations of owls were noted on the roads at night, probably as a result of the rodent explosion (Photo: Marna Herbst)

Although most outbreaks occurred in the first and second years after the drought, various insect eruptions were noted during and shortly after the drought. Banded Achaea (*Achaea catella*), a brown moth, erupted during the drought (*Achaea* species are known to erupt from time to time; Martins et al. 2015) and a small, black stinkbug (*Strombosoma impacta*) erupted in the first summer after the drought. In one area (just outside of KNP), termites (*Odontotermes* [Macrotermitinae]) were seen building sheeting on each and every *D. cinerea* tree in a large patch, and entirely debarking these trees (Figure 5). Termites building soil sheeting on trees were seen in KNP as well, but not as widely as during earlier droughts, as recorded by Braack (1995) for the 1982/1983 drought: 'One of my most vivid recollections, aside from the totally denuded areas…was the very impressive extent to which macrotermitine termites had covered with soil runways the trunks and branches of mopane and other trees in large areas of the northern KNP'.

Cases of malaria in humans also increased in the years after the drought. It is not clear why this may be the case and whether it can be attributed to the drought *per se*. A possible explanation may be that the anopheline mosquito species (vector species for malaria) experienced predator release (predators of mosquito larvae, e.g. predatory insects or frogs, recovering slower post-drought than the mosquito larvae, resulting in reduced predator control mechanism) and/or lack of competition one year after a drought. Similar patterns of malaria epidemics being associated or lagging droughts have been observed elsewhere (Gagnon et al. 2002; see Stanke et al. 2013 for a review of how malaria, and other diseases, are variably related to drought and post-drought events).

One of the respondents to this study involved in river monitoring indicated that certain fish species were significantly more common during the drought than in pre and post drought years. This included the southern barred minnow (*Opsaridium peringueyi*) in the Sabie River and three spotted barb (*Barbus trimaculatus*) in the Letaba River.

As has been observed in earlier droughts (e.g. O'Connor 1991), forbs exploded, with forbs dominating the herbaceous layer during the drought whenever a small rainfall event occurred and also in the first wet season after the drought (Figure 6) — during normal (or above normal) rainfall years, grass biomass would generally dominate. In some places large patches were dominated by one or two forb and forb geophyte species (e.g. *Albuca seineri*, Ground lily (*Ammocharis coranica*), *Indigastrum parviflorum, Sida* sp., *Hibiscus* sp., *Melhania* sp. covered certain patches), whereas in other areas a diversity of forbs occurred. Even though forb biomass was high, the species composition seemed similar to normal years. However, the forb geophyte, *Crinum minimum,* which only flowers for one to two days, was observed to flower only for the third time on record in the KNP during the drought, and also at a location not documented before. The ability of forbs to exploit soil moisture in bare patches and become so abundant was interpreted as forbs being 'released' from competition with grass (Siebert and Dreber 2019).

Temporal distribution of rainfall is critical

The temporal distribution of rainfall, and not just the absolute amount of rainfall, may have had a disproportionally large effect in terms of how mammal mortalities played out. It was suggested by some that key rainfall events at specific times buffered large mammal mortalities. The relatively large and wide-scale rainfall event in March 2016, may have been instrumental in reducing large mammal mortalities. This rainfall not only stimulated large-scale forb emergence, but possibly also allowed deciduous trees to retain their leaves for longer or even allowed for limited sprouting late in the growth season. It will be valuable to explore how rainfall distribution differed between the 2015/2016 and 1991/1992 droughts and whether such differences may be responsible for some of the differences in mortality rates (and species affected; "*Species-specific responses*" and "*Expect surprises - no two droughts are exactly the same*"). Fresh buffalo and hippo carcasses reported by rangers in the central districts of the KNP peaked between January 2016 and March 2016 (~60% of all fresh starvation-linked carcasses reported over 18 months were during these three months), which corresponded to the period when fence breakages were at their highest in the Skukuza staff village. One can speculate that without this seemingly

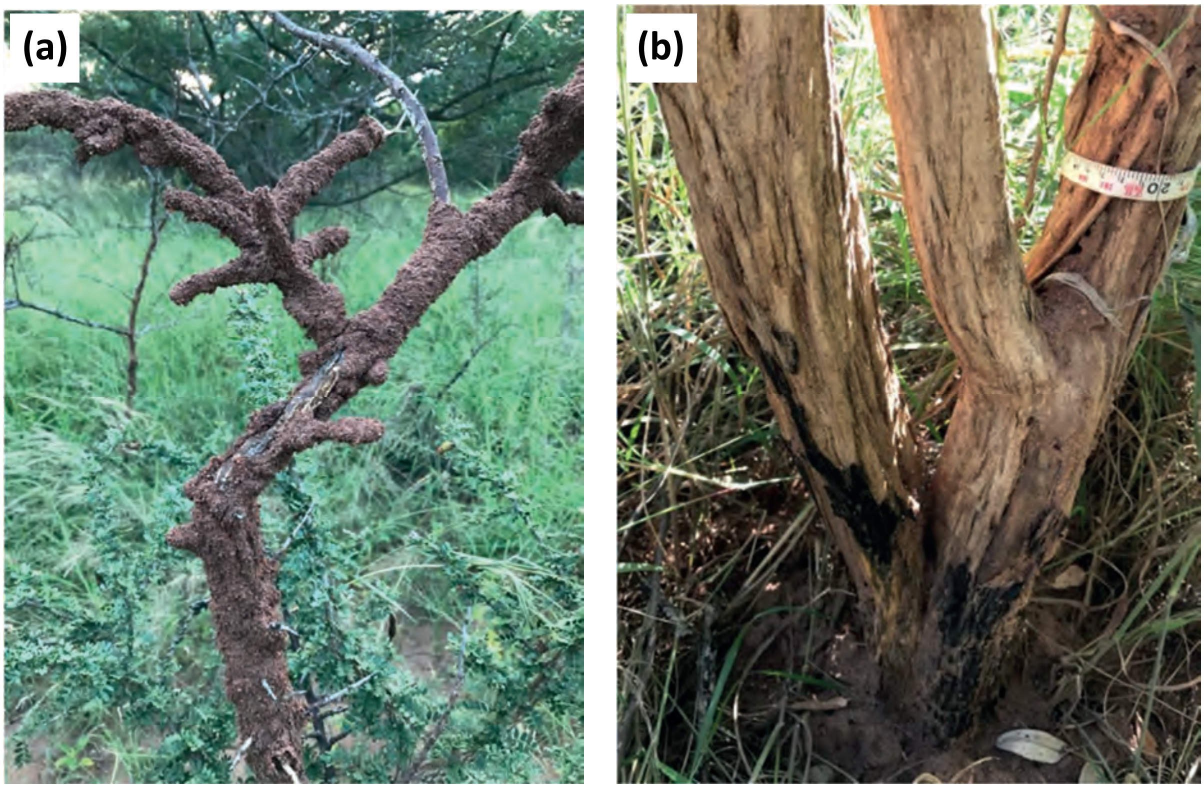

Figure 5: Termites of the genus *Odontotermes* (Macrotermitinae) were seen building sheeting on *Dichrostachys cinerea* (a), and debarking the tree, as can be seen when the sheeting came off (b) (Photos: Katherine Bunney)

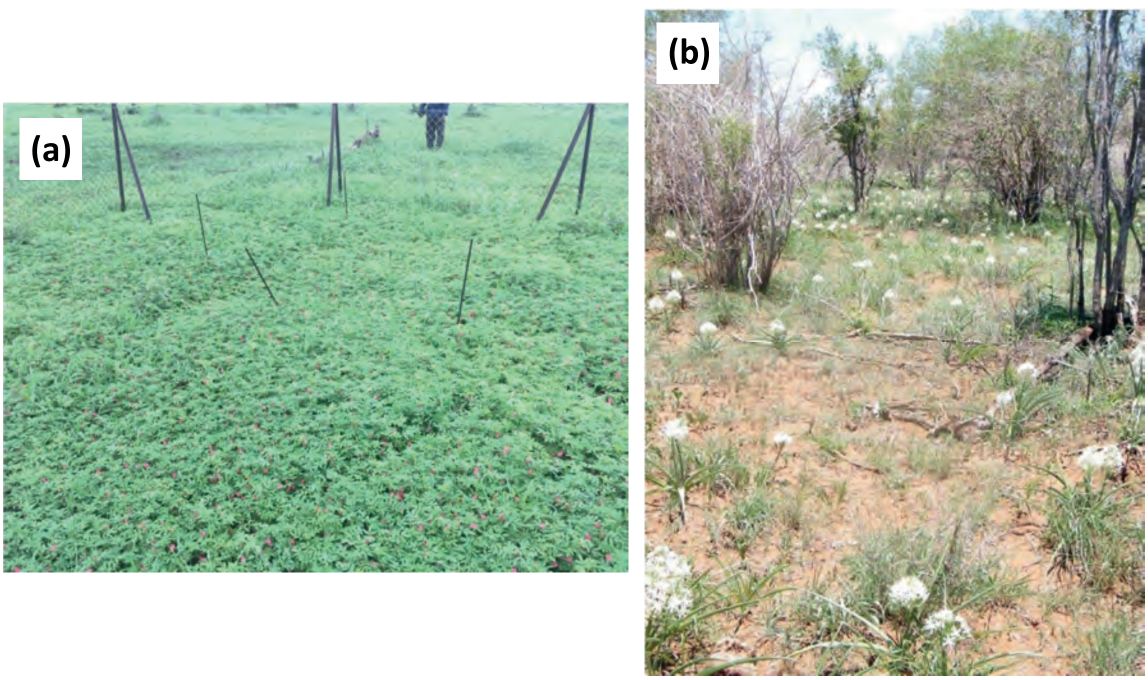

Figure 6: Forbs took advantage of soil moisture in bare patches during and after the drought after rainfall events — large stands of conspicuous forbs like *Indigastrum parviflorum* (a) and forb geophytes, like *Albuca seineri* (b), were often noticed in the first wet season subsequent to the drought. Grasses seemed to dominate the herbaceous layer again the following growth season (Photos (a): Kevin Wilcox; (b): Guin Zambatis)

Figure 7: Groundwater was critical during the drought, feeding persistent pools in seasonal streams that were utilised by wildlife and acted as refugia for aquatic biodiversity. Groundwater also sustained evergreen riparian trees throughout the drought, which were important sources of food and shade for other species (Photo: Izak Smit)

critical March 2016 rainfall event the drought may have played out differently and higher mortality levels recorded.

Anderegg (2013a) argues similarly for tree mortality, and that local context and rainfall distribution can play a significant role in tree mortality patterns during droughts.

Starvation- as opposed to thirst-induced mortality

Lack of food as opposed to lack of surface water was clearly and consistently reported as the reason for mortalities of large mammals (hippo, buffalo and white rhino) by various respondents (Walker et al. 1987; Owen-Smith 1996; Smit et al. 2020). The role that groundwater played in sustaining surface water as springs and pools in rivers was very noticeable and reported widely (Figure 7; see "*Groundwater creating drought refugia and affording buffering capacity"*).

Groundwater creating drought refugia and affording buffering capacity

Groundwater was a slow responder to droughts, as opposed to surface water sources that were not linked to groundwater and that consequently dried out quickly, in response to a lack of rainfall and extreme maximum temperatures increasing evaporation. Pools and springs played a critical role in providing drinking water for animals, acting as refugia for aquatic biodiversity, and sustaining larger trees in riparian areas around ephemeral streams with access to groundwater (Davies et al. 2013; MacLaughlan et al. 2017; Bogan et al. 2019).

Although groundwater was a slow responder to droughts and hence afforded some buffering capacity, it is also seemingly slower to recover after the drought as the period of below-average rainfall persists. Certain springs and rivers were reported to be drier three years after the drought than during the drought, suggesting that groundwater levels are still dropping in the absence of significant recharge events during this period. The lagged effect of groundwater dynamics obviously has serious implications if another drought follows in quick succession, which will result in various groundwater dependent ecosystems being affected. It is interesting to note that, as a result of continual decline in groundwater levels, crocodiles (*Crocodylus niloticus*) have three years after the drought started digging caves in river embankments in locations where water levels have dropped significantly and where water has become too shallow to cover them. It is therefore important to take cognisance of time lags and longer-term cycles when considering groundwater resources as a slow responder.

Lagged mortality of tall trees, e.g. Sycamore fig (*Ficus sycamorus*), leadwood (*Combretum imberbe*) and Natal mahogany (*Trichilia emetica*), was observed only two to three years after the drought. Respondents attributed these mortalities to the continual drop in the groundwater level beyond the reach of those trees' root zone (Singer et al. 2013), but it could also possibly be as a result of multiyear events and the hydraulic physiological deterioration of trees (Anderegg et al. 2013a, 2013b). Anderegg et al. (2013a) indicated that contrary to the expectation that surviving trees have weathered severe drought, surviving trees are actually more vulnerable to future droughts, because of accumulated xylem damage.

Changes in food resources utilised

Forage resources that are not normally utilised by herbivores, were utilised during the drought. This included various grazer species actively browsing or eating dropped leaves, as well as herbivores feeding on species usually considered unpalatable, e.g. buffalo grazing on invasive and unpalatable *Pennisetum sphacelatum;* elephant and buffalo actively browsing *Phragmites* reeds to stubble; giraffe browsing on apple leaf trees (*Philenoptera violacea*), which is usually not utilised and buffalo wading deep into water to browse on water lilies (*Nymphaea* sp.) (Figure 8). It is not clear how much energy herbivores can extract from these resources, but they may be critical resources during severe droughts. Their nutritional importance can be explored in future droughts, to determine whether these 'drought foods' act as critical 'bridging' resources or are only eaten in an attempt to alleviate hunger (or possibly to keep their digestive microflora active). Previous studies have found that mixed feeders like impala select more forbs during the late dry season when resources are generally more limited (van der Merwe and Marshall 2012), and considering the forb emergence observed after rainfall events during the drought and the first year thereafter, the role of forbs as a critical resource during droughts is likely underestimated and require additional research attention.

Isolated cases were observed of predators feeding on adult hippo and elephant calves, but it is unclear whether these animals died of drought and lions were opportunistically scavenging, or whether the lions were actively killing these individuals compromised by the drought (there is some circumstantial evidence that these animals were actively predated on in a few cases).

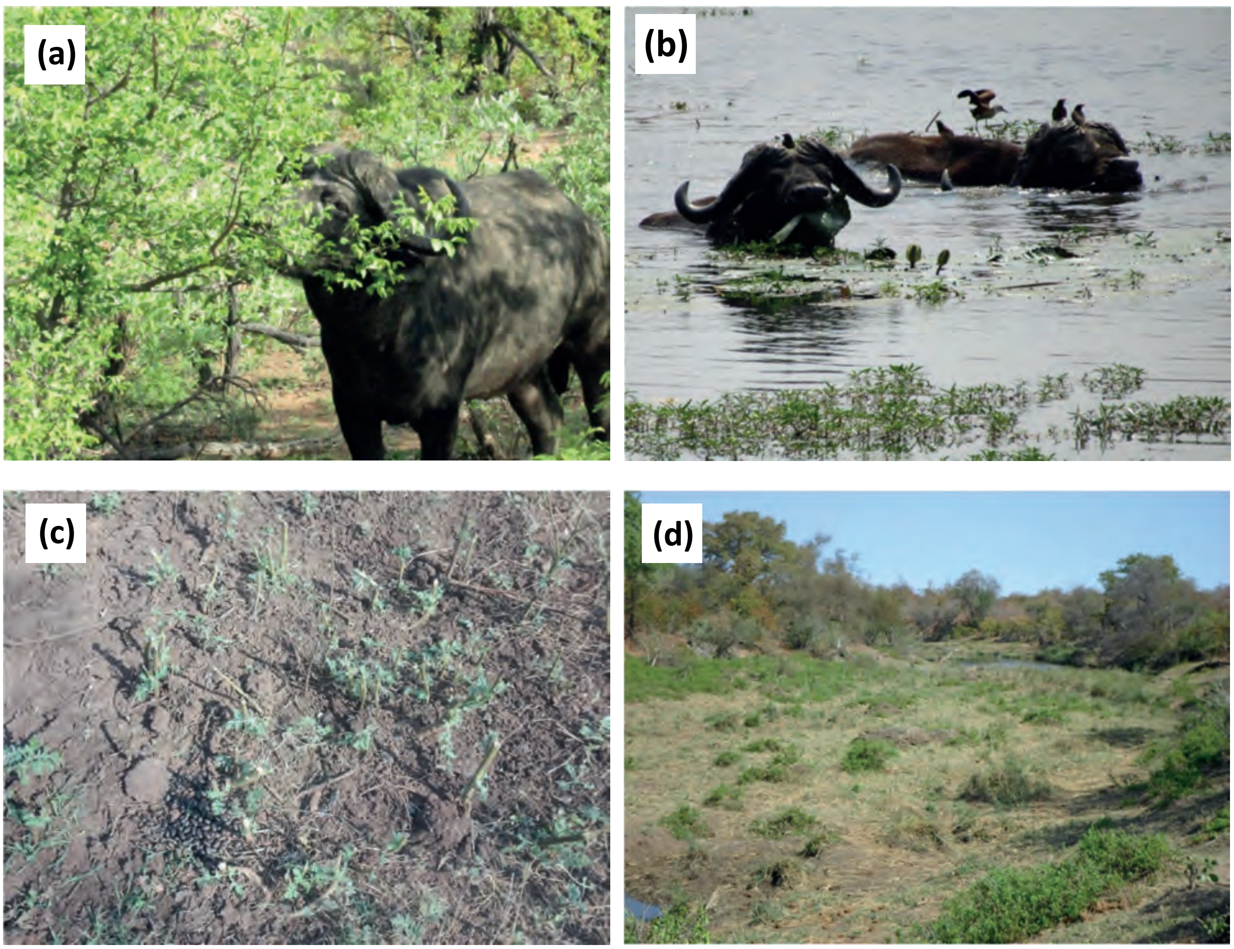

Figure 8: Herbivores utilised forage resources it would not normally utilise during the drought, like buffalo browsing (a) or wading shoulder height into a water body in order to forage on water lilies — two buffalo bulls were observed for an entire day displaying this extraordinary behaviour (b). *Parthenium hysterophorus*, an invading alien species that is widely regarded as inedible, because of its chemical properties that cause irritation and burning even just through touching (c), as well as *Phragmites* reeds (d) seemed to be grazed down to stubble in some areas (Photos: a, b: Jacques Venter; c: Thembeka Thwala; d: Izak Smit)

Behavioural changes of animals

Behavioural changes were observed for various species. These include lions spending extended periods around waterholes (Valeix et al. 2009); predators sharing food without displaying the normal rivalry (e.g. sharing of carcases by spotted hyena and leopard and by spotted hyena and black-backed jackal); large buffalo herds comprising of a couple of hundred individuals fragmenting into small groups of ~five animals, probably in order to gain access to adequate food, but rendering them more susceptible to predation (Funston and Mills 2006); individuals of some species becoming seemingly very tame (e.g. bushbuck and especially nyala in Skukuza staff village; civets on tourist roads and camps), whereas others showed more aggressive behaviour (buffalo cows towards humans on foot); earlier emergence time for various species in order to increase available feeding periods (e.g. hippo, bats and birds) (Frick et al. 2012); large crocodiles digging and sharing caves in river embankments in cases where water level in pools/springs have dropped too low to cover their bodies (see "*Groundwater creating drought refugia and affording buffering capacity"*).

Altered reproductive rates

Drought seemingly reduced reproductive rates of some species, with buffaloes having almost no calves in central KNP during the drought and the first year post-drought (possibly as a result of lack of conception), and impala having seemingly less lambs and more asynchronous lambing than usual (Ogutu et al. 2010, 2011). In 2019, approximately 21–22 months after the drought (gestation period of elephants), a large increase in elephant births was reported. Similarly, white rhinos did not calve during drought, but subsequent to drought, most cows have calved. Based on long-term individual elephant demography data for Amboseli, Kenya, Moss (2001) reported low birth rates for two years post-drought, and then when conditions improved again, females coming into oestrus, resulting in a synchronous wave pattern of births. Considering this, it can be expected that for various megaherbivore species in KNP, births may be synchronised in coming years, in a response to concurrent conception, as conditions became favourable after the drought (early 2017).

Rare and atypical disease occurrences

Various seemingly rare or atypical disease occurrences were noticed during the drought period, including the first ever diagnoses of tuberculosis (TB) in white and black rhino (*Diceros bicornis*) in KNP (Miller et al. 2018), as well as first ever human TB observed in a wild elephant (Miller et al. 2019). In addition, for the first time in many years African wild dogs were diagnosed with distemper (and an entire pack died as a result). Reports of mange were more common in predators than usual. A few elephant mortalities were noted after the drought where encephalomyocarditis (ECM) was expected (although not positively diagnosed), which is especially likely, considering that the host of this virus is rodents, which experienced a massive eruption after the drought ("*Drought and post-drought eruptions*"). An outbreak of ECM was also noted during earlier droughts in KNP (Grobler et al. 1995). Mass mortalities of laughing doves (*Streptopelia senegalensis*), possibly from pigeon paramyxovirus (diagnosed as such elsewhere in Mpumalanga Province adjoining KNP) occurred widely in central and southern KNP. Laughing doves have previously also been described as highly susceptible to, or reservoirs of *Paramyxoviridae*, especially during periods of stressful environmental conditions like droughts (Obanda et al. 2016). Interestingly no large scale anthrax outbreaks were experienced during the 2015/2016 drought unlike during the 1991/1992 drought (possibly linked to closure of artificial waterholes in the north of KNP, which would have allowed vultures to spread this disease quickly over large distances or, because the far north was not as dry as in 1991/1992).

It is difficult to make direct links between disease occurrence and drought, although malnutrition always has linkages to impaired immunity, and thus potential disease-related mortality. Furthermore, the concentration of animals around scarce water or food sources increases intra/interspecies contact rates, which could also play an important role in the extent of disease spread, compared with normal conditions. Co-infection during droughts may also be more common and lead to increased mortalities (Munson et al. 2008).

Expect surprises - no two droughts are exactly the same

Although there were similarities observed with previous droughts, and common lessons to be learned, there were also major differences. No two droughts are exactly the same and predictability remains relatively low between droughts, with surprises to be expected. One of the most apparent difference between the 1991/1992 and 2015/2016 droughts was the surprising lack of mortalities of mammal species that were noted to be the most sensitive during previous droughts (i.e. impala, bushbuck, warthog and kudu), and lower population declines for species that proved sensitive during both droughts (e.g. buffalo). Hippo was the exception with mortalities significantly higher in the 2015/2016 drought, compared with the 1982/1983 and 1991/1992 drought (see Smuts and Whyte 1981; Viljoen 1995b; Smit et al. 2020). The patchiness of the recent drought, the occurrence of rainfall at critical periods resulting in transient, but possibly critical 'green' flushes, and the closure of artificial waterholes, were the most common reasons presented for this surprising lack of large scale mortalities other than for the megagrazers (hippo and buffalo).

Management benefitted from learning from past droughts

Lessons from previous droughts resulted in proactive management actions that improved the situation during the 2015/2016 drought. The 1991/1992 drought 'forced' opportunities for cooperation with neighbours and relevant state departments, inter alia as river forums, some of which were still in operation during the 2015/2016 drought. The cooperation and self-organization between SANParks, not for profit organizations (like Association for Water and Rural Development, AWARD), water users and various government departments (former Department of Water Affairs) was paramount for managing the rivers at a

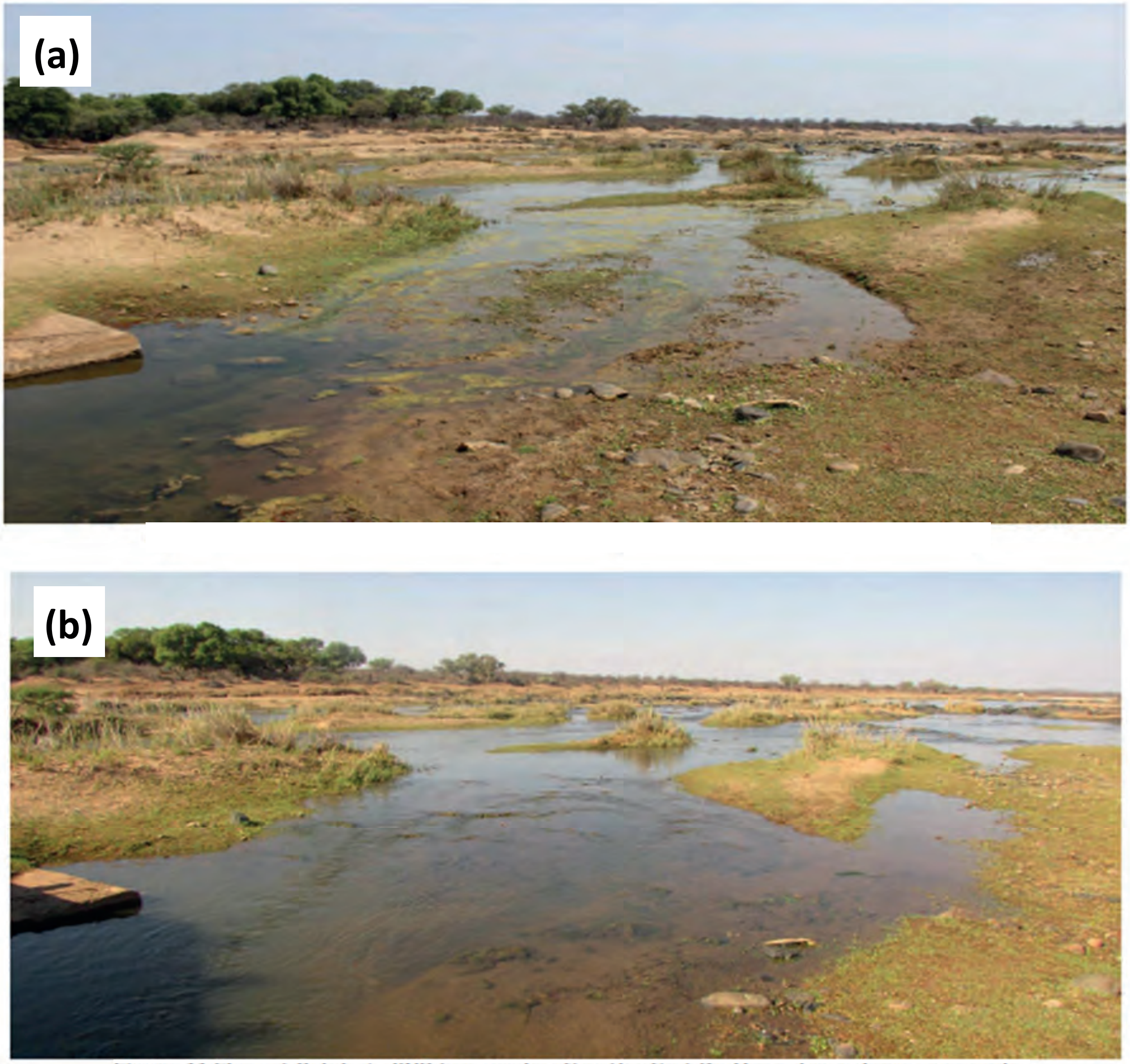

Figure 9: Flow in the Olifants River during the height of drought was about to cease (<0.4 cumecs when photo (a) was taken on 6 September 2016), but a water release from the upstream De Hoop Dam ensured better flows across the entire stretch of river below the release point (photo (b) was taken end of October after release from de Hoop dam on 14 October, resulting in improved flows of ~two cumecs). The Association for Water and Rural Development (AWARD) played a critical role in these processes and was a key strategic partner with SANParks and other stakeholders during the drought to ensure better flows were attained than during the 1991/1992 drought through upstream dams releases and strict irrigation restrictions (Photos from: Riddell et al. 2016)

catchment scale and mitigating the impact of the drought on the flow regimes (Figure 9; see e.g. Pollard and du Toit 2011; Riddell et al. 2016).

The rivers better sustained flows during the 2015/2016 drought than the 1991/1992 drought (based on archived flow data). The improved situation supports the strategic decisions taken after the previous drought to provide for rivers from dams (at that stage still to be built) in the upper catchments and the approach to manage rivers at the catchment-scale rather than the park-scale. Critical releases from upstream dams, and irrigation restrictions (up to 80%) were negotiated through organised and established networks, which improved the situation along extensive stretches of river to the shared benefit of water users (KNP, rural communities and commercial agriculture) (Riddell et al. 2016).

The density of artificial waterholes in KNP was reduced by closing approximately two thirds of the borehole-fed artificial waterholes (and many earthen and catchment dams) since the 1991/1992 drought (Gaylard et al. 2003; Smit 2013). There were various reasons for closing the waterholes, *inter alia* as a result of the perceived negative effects of wide-scale water provision during previous droughts (Walker et al. 1987; Owen-Smith 1996). Although hard to ‘prove’ the effectiveness of this management approach, many respondents explicitly commented on the lack of food rather than the lack of water as driver of herbivore mortality and some also ascribed the lower mortality rates during the 2015/2016 drought, compared with the 1991/1992 drought to the increased availability of reserve/buffer forage in water-remote areas, as a result of closing artificial waterholes (see Smit et al. 2020, for more detail). Regular movement between KNP (possibly for forage) and the adjacent private protected areas (possibly for water as these reserves have high densities of artificial waterholes) was observed for species like buffalo, whereas aerial census data also suggest significant regional movement of elephants between these areas, likely as a result of the creation of resource gradients, as a result of variable management approaches (Smit et al. 2020).

Drought as critical disturbance process

The drought played the role of a critical disturbance process, resulting in large-scale changes not observed as a result of the more frequently experienced top-down disturbance processes like fire, herbivory and predation. As such, the drought 'controlled' certain populations and 'reset' certain ecological trajectories, probably as part of longer inter-drought cycles:

- *Herbaceous layer:* In some locations an unpalatable perennial grass (*Bothriochloa radicans*) that dominated landscapes for a long period and that was resilient to manipulations of fire and herbivory regimes pre-drought, experienced high mortality during the drought and was subsequently replaced by a more palatable grass sward (dominated by *Urochloa mosambicensis*) (Thompson 2017; Wigley-Coetsee and Staver 2020). A similar phenomenon was observed in Hluhluwe-uMfolozi reserve, South Africa, where *Bothriochloa insculpta* and *Sporobolus pyramidalis* died during a drought, freeing up space for more palatable species that surged after the drought (Abbas et al. 2019).
- *Woody layer*: Sickle bush (*D. cinerea*), a woody encroacher species, experienced severe mortality and dieback during the 2015/2016 drought (Case et al. 2020). This was also observed in the 1991/1992 drought (Viljoen 1995a). Droughts seem to play an important role controlling the density and distribution of this encroacher species that otherwise seems rather resilient towards other disturbances like fire and herbivory (Figure 3).
- *Megaherbivores*: Because hippo and buffalo culling was ceased shortly after the 1991/1992 drought, the populations of these species increased to their highest ever-recorded densities in the park's recorded history in the year before the drought (2015). The drought acted as a natural population controller for these megaherbivore species that do not seem to be sufficiently predator controlled (Smit et al. 2020).
- *Below-average rainfall specialists*: observations suggest that some species may be responding positively to the prevailing drier cycle that already started before the 2015/2016 drought (e.g. blue wildebeest, black-backed jackal; see "*Species-specific responses*").

Droughts are part of savanna evolutionary history

Although the 2015/2016 drought was characterised by extreme conditions (low rainfall and extreme maximum temperatures over extended periods) (Figure 1; Malherbe et al. 2020), with many unusual patterns and processes observed across a range of scales and taxa, none of these were considered 'catastrophic'. It became clear through this assessment that droughts should be considered as part of the evolutionary history of savannas and that although savannas are strongly shaped by droughts, savannas also exhibit resilience and adaptation to these events, with droughts playing an important role in longer-term cycles (Figure 10; "*Drought as critical disturbance process*"). An example of the co-evolution of savannas with fire, herbivory and drought is provided by van Coller and Siebert (2019), where the negative effects of herbivore exclusion seemed to outweigh the effect of fire, herbivory and drought on herbaceous functioning.

Research gaps

One of the primary goals of this project was to use observations to provide an integrated and holistic perspective of a drought, but also to use this to identify knowledge gaps and stimulate future research in the ecology of drought. Below is a selection of key questions and knowledge gaps we identified based on the observations documented as part of this study:

- Impact of drought reverberated through the entire system from smallest to largest plants and animals. Therefore, this is a major ecosystem perturbation. However, what is a 'drought'? This was perceived to be a 'deep' drought, distinct from the usual annual variability in rainfall. How well do we understand the climatology of years of 'deep drought' as opposed to just a drier year? Are there any qualitative tipping points from ordinary to extraordinary ecosystem responses to rainfall deficits? How important are the rainfall conditions in the year preceding the 'deep drought'?
- KNP savannas seem resilient to drought, with no 'catastrophic regime shifts' to some alternative state. There was no widespread dieback of trees opening up the landscape as observed, for example, in some Australian savannas. The drought did not lead to extirpation of any influential large mammal species, nor, as far as we can say, of any smaller creatures. Is this unsurprising given the long history of episodic droughts in southern African savannas? Are African ecosystems generally resilient to severe droughts? What would be the effects of more protracted droughts or droughts in quick succession?
- Is the apparent resilience dependent on landscape scale? KNP is far larger than farms, or most conservation areas. How does drought scale, and how much resilience is available at smaller scales? Should droughts be managed differently at different scales (see e.g. Peel and Smit 2020)?
- The fundamental question of population ecology of what regulates populations looms large when observing the eruption of rodents, moths, queleas, and, amongst plants, the forbs. Such eruptions could provide insights into what regulates populations. For example, are rodent outbreaks the result of reduced predation, because of the decimation of snakes? Alternatively, increased food resources from the explosion of seeds from post-drought annual grasses and forbs? Does population regulation by disease change, because microbes thrive when their hosts are emaciated? We still know remarkably little about what regulates populations in nature. The unravelling of food webs, changes in the competitor

Figure 10: Sequence of photos showing drought and post drought responses in the Nwanetsi section, which was at the epicentre of the 2015/2016 drought in the South African Lowveld and Kruger National Park. Although droughts shape savannas at various spatio-temporal scales, these systems are resilient and evolutionarily adapted to droughts (Photos: Robert Bryden)

milieu, or availability of resources triggered by deep drought offer opportunities for better understanding of the complex regulatory processes in nature.

- Various species foraged on resources they would not typically consume (e.g. foraging on unpalatable species; grazers actively browsing). Are these critical resources that play an important role as bridging resource, or are the animals gaining little out of consuming these (i.e. do they forage on these resources out of desperation and to reduce hunger, or do they benefit nutritionally from consuming these resources)?
- Forbs dominate after rainfall events that occur during droughts and in the period directly after droughts. What is the role of forbs during droughts and do they function as a critical forage resource during and after droughts, both for grazers and browsers? (Linked to question above).
- Most drought research focuses on the amount of rainfall and not so much the temporal distribution of rainfall. Observations during the 2015/2016 drought seem to suggest that one rainfall event late in the summer season, as well as some smaller events throughout the season may have had disproportional effects. More research is needed to understand the effect of timing and distribution of rainfall and also the interaction of lower rainfall with extreme temperatures often associated with droughts.
- Small areas (refugia) can be of disproportionate importance during droughts. More research is needed on defining and understanding the characteristics, dynamics and role of these refugia as hotspots for survival during droughts and recolonisation nuclei after droughts. Similarly, the importance of heterogeneity to increase resilience during droughts should receive more research attention in order to inform climate adaptation strategies.
- What are the mechanisms behind tree mortalities (e.g. is it hydraulic, or starvation, or increased herbivory pressure) and what traits make trees vulnerable to drought? Some tree and grass species seemed to be more susceptible to drought effects than others were, yet the patterns were often also very patchy (e.g. individuals of a tree species would survive in one area, but die-off in another area close by). What are the traits of species that are more likely to die (e.g. are root-suckering species more likely to die?), and what conditions contribute towards differential survival rates within a species? Linked to the above, how extensive and why are large and mature trees exhibiting lagged mortality of a couple of years after droughts?
- The vegetation layer and large mammals are often relatively well monitored and as such drought effects on these taxa are often well represented in the literature (this Special Issue a point in case), but drought effects on almost all other taxonomic groups seem to be poorly studied/understood. For example, insects and food webs dependent on insects may collapse during droughts without being noticed, or without any data to quantify the extent. Similarly, reptiles, amphibians, arachnids, and possibly even birds are all poorly studied taxa in the context of droughts in savannas and there appears to be very limited monitoring data collected to understand what happens to these taxa during droughts, the length of recovery after droughts and the cascading effects of these population fluctuations. As such, very

little information is available regarding the resilience or vulnerability of these taxonomic groups if drought intensity and frequency is to increase in future.

- Termite activity seems to be increased (or is it just more noticeable?) during droughts. The dynamics and role of termites during droughts are as yet poorly understood, and how termite activity may interact with other variables (e.g. geology, vegetation structure). By poorly understanding termite activity during droughts a critical driver of drought dynamics may potentially be missed. For example, was termite ringbarking responsible for widespread mortality of *Dichrostachys cinerea* or was it the intrinsic properties of the plant?
- Limited information is available on how drought plays out on different geologies, catenal positions and disturbance histories (i.e. fire and herbivory regimes before and during drought). Are plants on clayey soils more vulnerable during drought, and do they recover faster when rains return? Observations from this study seem to suggest that the abiotic template and disturbance regimes are important contributors to drought dynamics. This may have important implications for conservation management.

Conclusions

Drought is a critical disturbance process that affects various taxonomic groups (from insects to megagrazers and forbs to trees), has impacts at various spatial and temporal scales and is highly interactive in nature. Some of the effects of the 2015/2016 drought in KNP were transient (e.g. various eruptions during and after the drought), whereas other effects were part of longer cycles (e.g. large-scale dieback and mortality of *D. cinerea* and hippos). Some effects were highly localised (trees of a particular species dying in a patch, whereas others of the same species and same size classes in close proximity did not die), whereas other effects and distributional shifts played out over larger scales (e.g. species observed that were never or rarely recorded in the park before). It was also clear that animals adapt behaviourally (extending foraging time; foraging on resources not otherwise utilised; fragmenting herds) and spatially (movement to drought refugia; increased distances travelled between forage areas and water resources). The effects of the drought were species specific (some species advantaged, some disadvantaged and some seemingly unaffected), often patchy and interacting with other processes (herbivory and fire history) and the underlying abiotic template (geology). The first wet season after the drought was incredibly dynamic, with many post-drought eruptions across various taxa, which seemed to 'normalise' within ~two years. From a management perspective, various productivity and biodiversity advantages were observed from the drought (e.g. mortalities of bush encroaching *D. cinerea* and replacement of dominant unpalatable *Bothriochloa radicans* grass with palatable *Urochloa mosambicensis*) and certain species are seemingly benefitting from the prevailing low rainfall cycle (e.g. blue wildebeest, black-backed jackal). The invertebrates, and the food web associated with them, were heavily affected with various crashes and eruptions associated with a range of invertebrate taxonomic groups. Reptiles, especially chameleons and snakes, were also seemingly heavily affected and are slow to recover to pre-drought densities. Considering the assessment presented here, and observing the photos of the extreme conditions experienced during the drought, as well as the post-drought responses, it highlights the resilience of savanna systems to cope with, recover from and reorganise as a result of these extreme events. It also suggests that some species may have evolved to exploit conditions that are most common during or immediately post-drought (the notion of 'drought specialists'). With return times of two or three decades, severe droughts are not unlike episodic fires in shrubland (e.g. fynbos) for which many plants show post-burn adaptations.

It is trusted that this assessment will stimulate drought research to formally test some of the observations and perceptions captured here, and lead to future drought episodes being welcomed as critical learning opportunities by scientists and funding agencies alike. We also trust that observations and photos contained as part of this project (see extended report by Smit and Bond (2020), which is richly illustrated with photos) will remind conservation managers in future of the 2015/2016 drought and reduce anxiety levels when the next drought occurs. Memory fades fast and depending on when the next severe drought is experienced, many of the 2015/2016 management and scientific generation may not be around (the dwindling generation that experienced the 1991/1992 drought were critical in providing perspective and reducing anxiety during the 2015/2016 drought). We found this project of collating drought related observations across many colleagues with many different interests and perspectives useful, because it allowed some collective reflection, co-learning and sharing between scientists, managers, rangers and guides. We encourage additional qualitative studies during future droughts to document observations and archive photos in order to increase the learning opportunities from these events and create a more holistic view of the many facets associated with droughts.

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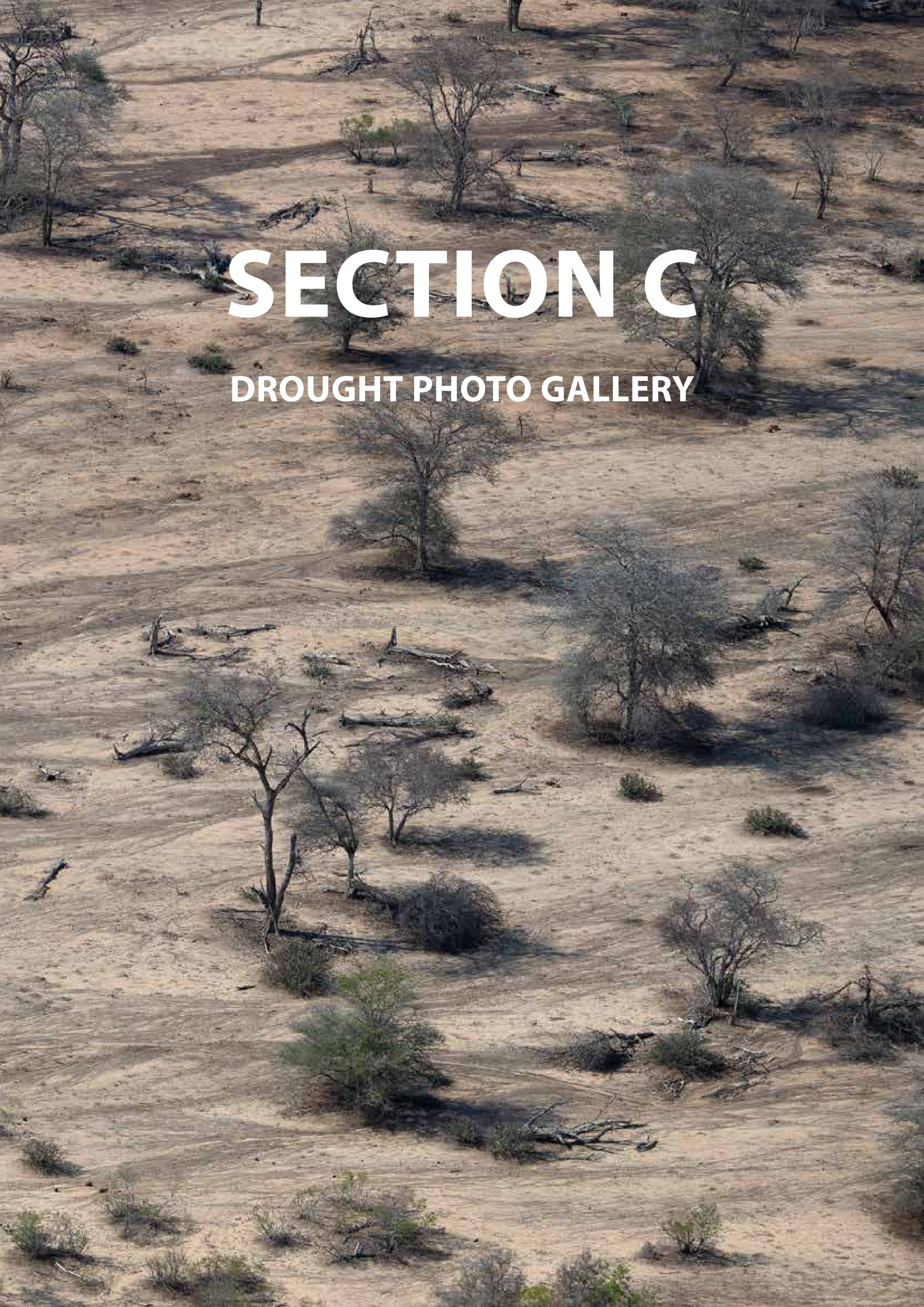
SECTION C

DROUGHT PHOTO GALLERY



Gallery of various photos taken during 2015/16 drought by Izak Smit (Scientific Services)

Soil differences next to the Nwaswitsontso river, with dead *Dichrostacys cinerea* skeletons prominently in the foreground.

Dichrostachys cinerea skeletons next to Nwaswitsontso river.

Drought revealing patterns not otherwise clearly visible, like rocks being "kicked out" of footpaths.

Large parts of Nwanetsi section was bare ground.

Impala foraging on fallen leaves from Jackalberry *Diospyros mespiliformis.*

Elephant digging for and exposing groundwater resources in seasonal steams.

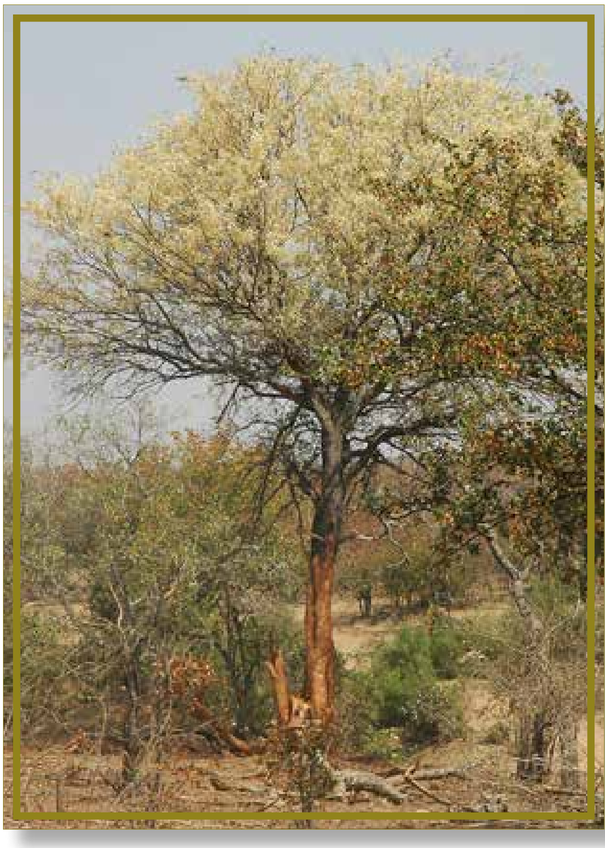
Lack of herbaceous layer revealing high densities of apple leaf *(Philenoptera violacea)* saplings/gullivers around Nwaswitsontso river.

Shade was an important resource on days of extreme heat and limited foliage.

Elephant dung around artificial waterhole illustrated how extensively elephants utilised these resources during the drought period.

A Sjambok pod (*Cassia abbreviate*) in flower despite the drought

Previous three photos: Areas around the waterhole at Talamati Bush Camp was denuded of any herbaceous layer.



Acacia nigrescens in full flower during the drought – some respondents commented on observing incredible flowering during the end of the drought (this has also been documented in the 1991/92 drought).

Vast landscapes around Timbavati river were denuded of herbaceous layer and intense elephant impact on *Acacia tortilis* was evident.

Emaciated hippo searching for food during daytime (close to Piet Grobler dam, Houtboschrand)

Grazing lawns fringing remaining water in the rivers (top: Olifants river; bottom: Letaba river) were important resource areas for herbivores

Top and bottom: Effects of rainfall runoff from roads were visible and attracted browsers (and grazers – see earlier in report) to roads.

Not all areas were equally affected by drought – e.g. the area around the Tsendse river close to Mooiplaas picnic site possibly had some buffering effect (this area received disproportionally high rainfall in March 2016 during the height of the drought and water and forage resources were less limited than in other regions).

Sometimes patches of better resources were heterogeneously available in a landscape – e.g. the green mopane trees above are probably due to localised soil differences which influence the soil moisture availability.

Top and bottom: Patches of seemingly better forage quality were exploited by animals (elephants foraging in "green islands" of mopani in a seemingly "brown sea" of mopane.

The far north of the KNP had better rains than the remainder of the park during the 2015/16 drought. As a consequence, the buffalo herds in the far north did not fragment into smaller herds as was the case in the central KNP where the drought had its epicentre. A few buffalo calves were even observed in the far north. This clearly illustrates the importance of large and contiguous protected areas as droughts are often spatio-temporally heterogeneous and refugia may play an important role in making ecosystems resilient to extreme events like droughts.

Levuuvhu river

Top and bottom: Dust storms and dust devils were frequently observed, which could turn the light quality to dark and murky.

Series of photos indicate the importance of grazing/hippo lawns that developed in the rivers, often fringing the surface water. These were utilised by grazers (e.g. hippo, zebra, blue wildebeest, warthog), some browsers (e.g. kudu) and mixed feeders (impala and even elephants were seen seemingly utilizing these grazing lawns).

Rhino middens could potentially act as resource hotspots due to the addition of nutrients and moisture resulting in green and nutritious patches on a very small scale.

Two scenes from north of Satara on the road to Olifants.

Scene next to Nwaswitsontso river – impact of drought on predators and trees (possibly neutral or positive in the short term) as opposed to mega-grazers and herbaceous layer (negative in the short term)

Previous three photos: Elephant impact, including uprooting and debarking of woody vegetation, was very noticeable. Both large trees and bushes seemed to be affected.

Previous three photos: Scenes during the drought from the mopane veld.

Some river pools were maintained by groundwater resources throughout the drought – scene from Shingwedzi river

Bottom and top: Isolated rainfall events led to bare patches often being covered in forbs, sometimes of mono-specific species, which often would wilt again in subsequent days of extreme heat.

Lack of herbaceous cover, but with woody vegetation still in leaf – photo taken during summer months from Nkumbe mountain between Lower Sabie and Tshokwane.

Late during the summer season of the drought (March 2016) rainfall was widely reported in KNP, resulting in a green flush. These rainfall events sometimes resulted in trees flushing again, and probably also resulted in trees retaining their leaves for longer. It was hypothesized that especially the March 2016 event, but also other smaller such events or less widely occurring events during the drought, may have played a critical role in reducing the mortality rates of some species like impala, kudu, warthog and bushbuck. These events may have created important temporal refugia.

Unusual behaviour noticed for buffalo herd close to Mpondo dam – this herd clumped into a group on a (seemingly) dry pan in the middle of a warm day. It is unclear whether there may have been thermal advantages in this behaviour as it looks like the contrary.

Gallery of photos by Cathy Greaver (Scientific Services) during aerial surveys

Crocodiles feasting on a dead hippo - many hippos died during the drought and many predators and scavengers were seen on hippo carcasses both in the water and outside of the water (see elsewhere in report).

Gallery of photos taken by Pauli Viljoen (Scientific Services)

Gallery of photos (including fixed point photo sequence) by Robert Bryden (section ranger: Nwanetsi section)

23 August 2016

7 December 2016

28 February 2017

29 March 2017

24 May 2018

Dust storms were common during drought period, often leading to dark and murky atmospheric conditions.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