A SYNOPSIS OF FIELD AND REMOTE SENSING BASED METHODS FOR STUDYING AFRICAN ELEPHANT (*LOXODONTA AFRICANA*) IMPACT ON WOODY VEGETATION IN AFRICA

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Abstract. African elephants (*Loxodonta africana*) negatively influence woody vegetation, causing structural changes to ecosystems. Field-based survey methods used to monitor elephant impact, while valuable, are costly and time-consuming to execute. By applying distance-sampling techniques such as remote sensing technology, inaccessible areas can be surveyed. This overview provides insight into methods used by scientists to determine the impact of elephants on woody vegetation in sub-Saharan Africa. Data were sourced from a variety of research databases. Findings indicate that 87% (n = 92) of the reviewed studies used field-based methods and 13% (n = 14) used remote sensing-based methods. We explore the national affiliations of the lead and the last authors of the reviewed studies and the scientific journals that published them. Field-based is the dominant method used in the majority of published studies on elephant impact. The majority of these studies were published in European and American journals, instead of African journals, which are less represented. However, the majority of the lead and last authors' affiliations for both field-based and remote sensing based methods are affiliated with African institutions. We conclude that there is a need to improve the integration of remote sensing techniques into conservation and other ecological fields.
Keywords: *savanna, satellite imagery, national affiliation, accessibility, reviewed studies*

Introduction

African elephants (*Loxodonta africana*) are found in sub-Saharan Africa (Blanc et al., 2007), where they occupy savanna ecosystems, dense forests, Sahelian scrub and deserts (Nowak, 1999). Based on genetic information, taxonomists suggest that there are two sub-species of the African elephant namely, the forest elephant and the savanna elephant. Current literature indicates that there is no detailed knowledge available on the distribution of these sub-species or the presence of potential hybrid populations (Mondol et al., 2015). Savanna elephants are predominantly found in eastern and southern Africa, while the forest elephants are found mainly in the Congo Basin of Central Africa (Thouless et al., 2016). In this study, we considered African elephant as a single species found in sub-Saharan Africa (East, Central, West and Southern Africa).

Elephants, in general, utilize a wide range of landscape types when foraging. The distribution of resources across landscapes influences elephant home range use and size. Individual home ranges may include a variety of landscapes and ecosystems (Grainger et al., 2005). A home range is defined as an area traversed by an individual in its normal activities of food gathering, mating and caring for young (Burt, 1943). Elephant feeding

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behavior, densities, interactions with other herbivores, associated ecological and environmental factors such as fire damage, rainfall patterns, and plant growth rates, all influence elephant impact on vegetation (Dublin et al., 1990; Ben-Shahar, 1996b; Ferguson, 2014).

Adverse impacts associated with African elephants on ecosystems include reducing tree heights and densities, which leads to structural changes in the woody layer (Ben-Shahar, 1998; de Boer and Kohi, 2008). Changes in overall vegetation composition lead to a decline in biodiversity (Kelly, 2000). Guldemond (2006) found that elephant impacts in closed woodlands create canopy gaps, leading to reduced recruitment of young trees. Elephants require a daily average fresh food intake of approximately 173 kg across both the wet and dry seasons (Ruggiero, 1992). Since they feed mainly on woody plants, tree mortalities are common in areas they frequent. Woody plant species composition, tree species distribution, tree size, tree age, feeding preferences and habitat availability influences the consumption of woody vegetation by elephants (Gadd, 2002; Van Staden et al., 2016).

Protected areas are representative of natural vegetation that previously occurred in the broader vicinity around the protected area. This includes woodland spatial distribution, composition, and structure without anthropogenic influences (Guy, 1976; Gandiwa et al., 2011). The vegetation type, rainfall (Gandiwa and Kativu, 2009), management and conservation strategies and interventions (Hamandawana, 2012), differ for each protected area. Smit and Ferreira (2010) state that the availability and distribution of water sources remain different from one area to another, influencing elephant movement patterns. Variability between areas and their sizes, coupled with different elephant densities leads to fluctuating distribution patterns and intensities of elephant impact. The numbers of elephants have been steadily increasing in many protected areas in the sub-Saharan region, raising concerns of their impacts to biodiversity (Van Aarde et al., 2006; Van Aarde and Jackson, 2007). The focus on elephant management in many protected areas has been on their numbers in relation to the size of the area they occupy. According to Van Aarde et al. (2006), this approach gave rise to the establishment of many artificial water points, which modify the movements and home ranges of elephants.

Available methods for managing elephant populations include culling, relocation, and the use of contraceptives (Pimm and Van Aarde, 2001; Rubio-Martínez et al., 2014). Elephant culling remains a highly debated and sensitive subject in the scientific community (Mackey et al., 2006; Balfour et al., 2008; Lotter et al., 2008). Relocation of elephants is not a permanent option, but a temporary solution that can present adverse effects on the breeding behavior of female elephants (Raath, 1999). Relocated animals that breed can often not be accommodated by the parks or reserves they are moved to (Rubio-Martínez et al., 2014). Laparoscopic vasectomy is a costly contraceptive technique applicable to free-ranging male elephants. The long-term effects of this type of contraception are yet to be studied to determine how the elephant population demographics and dynamics are influenced (Rubio-Martínez et al., 2014). Additional contraceptive techniques available to wildlife managers for free-ranging elephant cows include pregnancy termination, the use of estrogen implants and immunocontraception (Poole, 1993; Whyte and Grobler, 1998). While these contraceptive techniques reduce population growth rates, they are often impractical and expensive to implement (Whyte et al., 1998).

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An increase in the number of studies that investigates the impact of elephants on vegetation structure and dynamics has been noticed over the three past decades (Ben-Shahar, 1996a, 1998; Shannon et al., 2011; Van Staden et al., 2016). Moreover, the impacts of elephants on vegetation has increasingly become one of the main concerns for environmental and protected area managers (Baxter and Getz, 2008; Wiseman, 2001). We identified two review papers on the impacts of elephants on vegetation in Africa (Guldemond and Van Aarde, 2008; Guldemond et al., 2017). Guldemond and Van Aarde (2008) reviewed 21 studies between 1961 and 2005 from 14 study sites in Africa. Although no opinion or broad generalizations were made on elephant management from the reviewed studies, there was no doubt that elephants have an effect on woody vegetation and that high elephant densities could result in adverse impacts. Guldemond and Van Aarde (2008) also highlighted the lack of published information on the effect of elephants on vegetation.

A current review paper by Guldemond et al. (2017) that looked at 51 peer-reviewed articles concluded that elephants have a significant influence on vegetation by changing tree structure and abundance. No overall adverse cascading effects for species that share space with elephants were reported. Both these reviews focus on the impact of elephants and not the methods applied. This makes it necessary to provide an overview of the studies and techniques that have been used to quantify the impacts of elephants on the environment. This would provide useful information for conservation managers, and would also identify opportunities for further research into practical and time-efficient methods for studying the impact of elephants on vegetation.

This paper aims to provide an insightful review of the types of methods used by different peer-reviewed studies to quantify and detect the impact of elephants on woody vegetation in sub-Saharan Africa from 1970 to 2017. For this paper, we grouped the studies into two different categories, a field-based (FB) approach and those that used a remote sensing-based (RS) approach. Field-based approaches involve the physical collection of detailed data using certain tools and techniques in the veld (Zimmerman, 2014). Remote sensing approaches provide a variety of imagery known for their different spectral, spatial, radioactive and temporal characteristics that are applicable for use in broad vegetation studies (Xie et al., 2008).

Our review provides information on the geographic location of each study (location of study area and spatial scale of research), the national affiliation of the lead and the last authors and whether the publication is local (within Africa) or international (outside the African continent). We further explore studies that use remotely sensed data in more detail and highlight the challenges and limitations of field-based and remote sensing-based methods.

Materials and methods

Database and literature search

For this review paper, we only included studies that related to the African elephant and made no distinction between forest and savanna elephants. We were interested in studies that explored the damage or impact of elephants on woody vegetation in conservation and protected areas. We have, therefore, excluded studies on immune-contraception, distribution, movement, population and densities of elephants. However, we sourced information on the densities of elephants in the sub-Saharan region from Thouless et al. (2016). Our review includes English; peer-reviewed articles containing

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original research from 1970 to 2017. This review excludes thesis documents and dissertations. We considered all studies from the four sub-Saharan regions (west, east, south and central Africa).

Relevant articles were identified using different keywords in different databases. Data were sourced from the ISI Web of Science during May 2018. “African elephant” was the first keyword used to retrieve studies published on elephants from the database. Two thousand two hundred and fifty-three (n = 2 253) studies dating back to 1972 were retrieved. We refined our search using keywords such as “elephant damage”, “elephant impact” and “woody vegetation” which resulted in 26 studies that matched these criteria. Since the Web of science database only lists articles between 1972 and 2018, we decided to search other scientific databases.

An additional list of 507 studies was sourced from Nexus, SA e-Publications, EBSCOHost, ScienceDirect, Taylor & Francis, ProQuest, BioOne, and SpringerLink using the keywords “elephant damage, “elephant impact,” “woody vegetation” and “Africa.” Studies from these electronic databases, repositories and search engines dated back to 1970, which is two years earlier than the data retrieved from the Web of Science website. Eighty-one (n = 81) studies from this search were relevant and were included in this review. Based on all the retrieved studies (n = 2 253 from ISI Web of science + 507 from above listed additional databases = 2 760), a sample of 106 (n = 26 + 80 = 106) studies were used for this review paper. These studies matched our search criteria and were grouped according to which part of the sub-Saharan region they belong to (eastern, central, western or southern Africa).

From the 106 studies, we extracted the year of publication, authors, methods used, country and location of the study area, and publishing journal and its location. We broadly recognized two types of methods from these studies, field-based (FB) and remote sensing-based (RS). Field-based methods have been extensively used due to their robustness in providing a widely reliable dataset (Buchanan et al., 2013). According to Liverman et al. (1998), field-based studies are generally not sufficient to quantify and analyze patterns of spatiotemporal change at an aggregated level. On the other hand, remote sensing techniques provide useful data sources for quantitatively measuring the dynamics of change processes at the landscape scale by analyzing change trajectories (Mertens and Lambin, 2000). Since this paper intends to provide insight into the types of methods used by scientists to study the impact of elephants on woody vegetation in Africa, we further discuss the limitations of each of the two approaches (field-based and remote sensing-based).

Content analysis

We determined the number of studies using either field-based or remote sensing-based methods per African region. Based on Thouless et al. (2016) report that estimated densities of African elephants in sub-Saharan Africa, we compared the relationship between the number of studies and the estimated number of elephants per region. Information on the national affiliation of the lead and the last author (Bhattacharya, 2010) was extracted for each of the studies. We included the lead author on the basis that the first author is generally the person who did most of the work, while the last author was included on the basis that he or she may have contributed to the work as a supervisor affiliated to an academic institution (Bhattacharya, 2010). We further identified the scientific journals that published all the studies included in this review and whether these were local (within African) or international (outside Africa).

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Results

For this review, we identified peer-reviewed studies on the impact of African elephants on vegetation in the sub-Sahara region, which is the natural distribution range for African elephants (Thouless et al., 2016) (*Fig. 1*). A total of (n = 106) papers was retrieved from different scientific databases (*Table 1*). Eighty-seven percent (87%) of the studies used field-based methods (n = 92) while 13% (n = 14) applied remote sensing-based methods for data collection. A list of all peer-reviewed studies, both field-based and remote sensing-based published between 1970 and 2017 is included as *Appendix A*. Field-based studies date back to 1970 and the oldest study that used remote sensing data to study elephant impact on vegetation was done in 1997, which is two decades after the field-based studies. A list of the estimated number of elephants (Thouless et al., 2016) for countries in Sub-Saharan Africa is included as *Appendix B*.

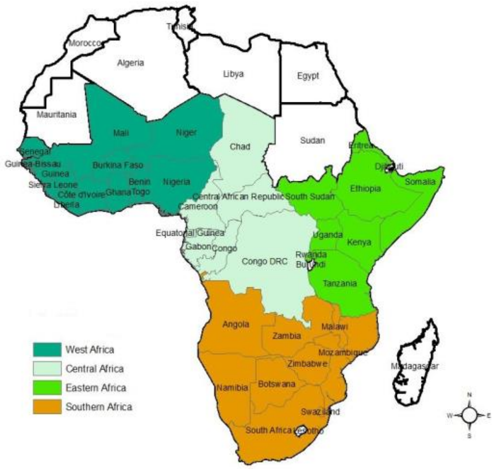

Figure 1. *Distribution map of African elephants in the west, east, south and central countries of the sub-Saharan region in Africa (ESRI, 2014)*

Table 1. *A number of peer-reviewed papers retrieved from different databases*

Database	Retrieved articles	Relevant articles in the sample
BioOne	14	7
EBSCOHost	9	5
ISI Web of Science	2253	26
Nexus (NRF Research)	12	12
ProQuest	49	13
SA e-Publications	55	6
ScienceDirect	203	16
SpringerLink	65	10
Taylor & Francis	100	11
TOTAL	**2760**	**106**

Field-based and remote sensing based methods

We determined countries with records of field-based and remote sensing-based studies and the number of elephants in each country (*Table 2*). Ninety-two (n = 92) of the field based studies are located in Africa, and one study was done in Gal Oya National Park, Sri Lanka (Ishwaran, 1983). This study is excluded in *Table 2* since it was not done in an African park or reserve. Another study area located in East Africa

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was not specific to a particular reserve or national park (Laws, 1970). Since we could not individually assign it to one specific study location, we have also excluded it from *Table 2*. Fourteen (*n* = 14) remote sensing-based studies were identified, and only one was located in Africa and not specific to a particular reserve or national park (Duffy and Pettorelli, 2012), and is therefore not included in the data represented in *Table 2*. There is a study that was done in Borgu game reserve, Guinea (Afolayan, 1976) on the impact of elephant activities on woody vegetation, and according to Thouless et al. (2016), there is no record of estimated elephant numbers for the country.

Table 2. *List of countries with a record of field-based and remote sensing-based studies and the number of elephants*

Region	Country	No. of FB*	% of FB*	No. of RS**	% of RS**	No. of elephants
West Africa	Burkina Faso	3	3	0	0	6 850
West Africa	Benin	1	1	0	0	2 984
West Africa	Ghana	1	1	0	0	994
West Africa	Guinea	1	1	0	0	0
Southern Africa	Botswana	10	12	5	38	131 626
Southern Africa	Zimbabwe	20	23	2	15	82 630
Southern Africa	Zambia	1	1	1	8	21 967
Southern Africa	South Africa	30	35	3	23	18 841
Southern Africa	Mozambique	1	1	0	0	10 884
Southern Africa	Malawi	1	1	0	0	1 307
Central Africa	Cameroon	1	1	0	0	6 830
Central Africa	Chad	1	1	0	0	794
Eastern Africa	Tanzania	10	12	0	0	50 433
Eastern Africa	Kenya	5	6	1	8	22 809
Eastern Africa	Uganda	3	3	1	8	4 923
Eastern Africa	Rwanda	1	1	0	0	88
		86	**100**	**13**	**100**	**354 126**

*Field-based studies, **Remote sensing-based studies

We compared the relationship between the top ten African countries with the highest number of elephants to the number of studies from each one of them (*Fig. 2*). We also summarised the type of data used in the remote sensing-based studies (*Table 3*).

Affiliation of the lead and the last author for FB and RS based methods

The majority of the articles' lead and last authors for both field-based and remote sensing-based methods are affiliated with institutions located in South Africa (26%). The United States of America follows South Africa with 17%, United Kingdom and Zimbabwe with 10%, and the rest of the other countries below 3% (*Fig. 3*). There is a relatively equal distribution of lead: last authors ratio affiliations in all the countries, except for Botswana, Netherlands and Uganda with higher numbers of last author affiliations: 3%: 2% for Botswana, 1%: 0% for the Netherlands and 3%: 1% for Uganda.

The highest percentage (6%) of lead and last authors affiliated with institutions in the United States of America were for studies that used remote sensing-based methods. This is followed by Botswana, South Africa and the United Kingdom with 2% each and the rest of the other countries at below one percent. Field-based methods were applied to 73% of the studies compared to 27% for the remote sensing-based methods (*Fig. 4*).

All studies, both field-based and remote sensing-based were published in 43 different journals. Eighty-four percent (*n* = 36) were in international journals, and 16% (*n* = 7) were published in local journals (*Table 4*).

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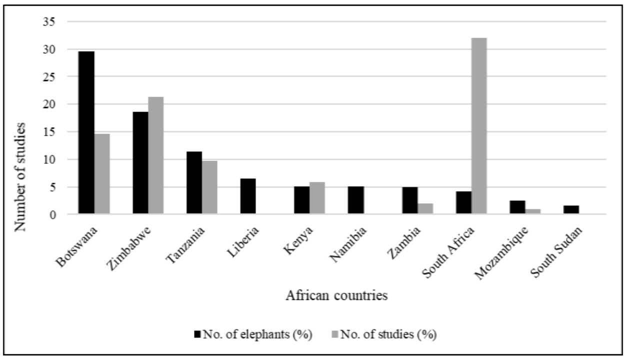

Figure 2. *The percentages of field-based and remote sensing-based studies in relation to the estimated percentage of elephants for the top ten African countries*

Table 3. *Summary of studies that applied the remote sensing-based method and the type of data used*

Satellite data	Number of studies	Percentage	Study Objective
Landsat TM	2	14	Impact of management strategies
Landsat MSS	1	7	Vegetation change over time
NDVI	2	14	Greeness versus elephant densities
MODIS	1	7	Piosphere effects
3-D	2	14	Vegetation structure
SPOT+NOAA+AVHRR	1	7	Ecological feature recognition
Aerial	2	14	Vegetation change over time
Aerial+SPOT	1	7	Vegetation change over time
Landsat+CORONA	1	7	Grazing pressures
Landsat+ETM+OLI	1	7	Impact of climate, fire and elephants
	14	**100**	

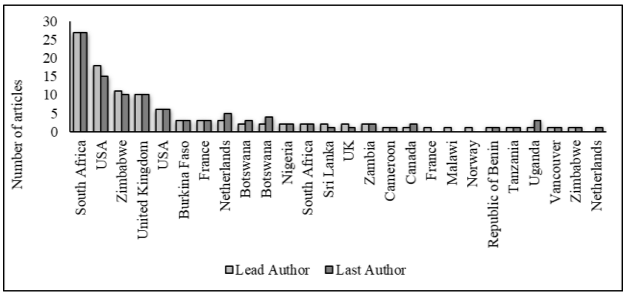

Figure 3. *National affiliation of lead and last authors from 106 reviewed papers*

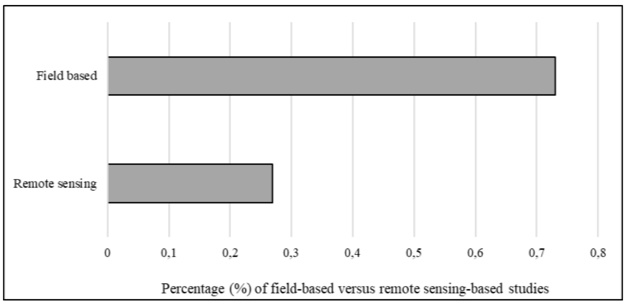

Figure 4. *The difference between studies that used field-based and remote sensing-based methods*

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Table 4. *Names of scientific journals where each of the reviewed studies were published*

	Name of Jnl.	Country	FBO**	RS***	All studies	Local	Intern.*
1	Jnl. of Tropical Ecology	United States	13	0	13	0	1
2	African Jnl. of Ecology	England	11	1	12	0	1
3	South African Jnl. of Wildlife Research	South Africa	7	0	7	1	0
4	Biological Conservation	England	5	1	6	0	1
5	Koedoe	South Africa	6	0	6	1	0
6	Ecological Applications	United States	4	0	4	0	1
7	Oikos	Denmark	4	0	4	0	1
8	Biotropica	United States	3	0	3	0	1
9	Ecography	Denmark	2	1	3	0	1
10	Ecology	United States	2	1	3	0	1
11	Int. Jnl. of Remote Sensing	England	0	3	3	0	1
12	South Africa Jnl. of Botany	South Africa	3	0	3	1	0
13	Int. Jnl. of Biodiversity and Conservation	?	2	0	2	0	1
14	Jnl. of Applied Ecology	England	1	1	2	0	1
15	Jnl. of Arid Environments	United States	2	0	2	0	1
16	Jnl. of Ecology	England	2	0	2	0	1
17	Jnl. of Vegetation Science	England	2	0	2	0	1
18	Pachyderm	Kenya	2	0	2	1	0
19	South African Jnl. of Science	South Africa	2	0	2	1	0
20	Tropical Ecology	India	2	0	2	0	1
21	Ambio	Sweden	1	0	1	0	1
22	Austral Ecology	Australia	1	0	1	0	1
23	Biodiversity and Conservation	Netherlands	1	0	1	0	1
24	Conservation Biology	United States	0	1	1	0	1
25	Ecological Research	Japan	1	0	1	0	1
26	Ecosystems	United States	1	0	1	0	1
27	Environmental Modeling and Assessment Jnl.	Australia	1	0	1	0	1
28	Forest Ecology and Management	Netherlands	1	0	1	0	1
29	International Forestry Review	England	1	0	1	0	1
30	Int. Jnl. of Applied Earth Observ. & Geoinfo	Netherlands	0	1	1	0	1
31	Int. Jnl. of Environmental Sciences	England	1	0	1	0	1
32	Jnl. of Animal Ecology	England	1	0	1	0	1
33	Jnl. of Ecology and the Natural Environment	?	1	0	1	0	1
34	Kirkia	Zimbabwe	1	0	1	1	0
35	Land	?	0	1	1	0	1
36	Plant Ecology	Netherlands	1	0	1	0	1
37	Proceedings of the National Academy of Sciences	USA	0	1	1	0	1
38	Regional Environmental Change	?	0	1	1	0	1
39	SpringerPlus	Germany	0	1	1	0	1
40	Systematics and Geography of Plants	Belgium	1	0	1	0	1
41	Transactions of the Royal Society of RSA	South Africa	1	0	1	1	0
42	Tropical Pest Management	England	1	0	1	0	1
43	Vegetatio / Plant Ecology	United States	1	0	1	0	1
			92	**14**	**106**	**7**	**36**

*International, **Field-based, ***Remote sensing, ?Unknown, Geoinfo-Geoinformation, Int.-International, Jnl.-Journal, RSA-Republic of South Africa, Observ.-Observation

Discussion

Southern Africa has the highest number of elephants on the African continent, with an estimated 71% (n = 293 447) of all the elephants on the continent. East Africa has 21%, Central Africa 6% and West Africa 3% (Thouless et al., 2016). The highest estimated elephant distribution range of 1 325 998 km² is in southern Africa, followed by 880 648 km² for East Africa, 783 085 km² for Central Africa and 142 500 km² for West Africa.

The top ten countries with the highest number of elephants include Botswana (131 626), Zimbabwe (82 630), Tanzania (50 433), Kenya (22 809), Namibia (22 754),

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Zambia (21 967), South Africa (18 841), Mozambique (10 884), South Sudan (7 103) and Gabon (7 058) (*Table 2* and *Appendix B*).

Our results indicate that South Africa produced the highest number of studies on the impact of elephants on woody vegetation and yet has a lower number of elephants compared to Botswana, Zimbabwe, and Tanzania. Botswana has the highest number of elephants but not as many research studies (15 studies) compared to South Africa (33) and Zimbabwe (22). According to Blanc et al. (2007), elephant numbers are increasing in Southern Africa, which may result in an irreversible impact on vegetation, especially in enclosed protected areas with high elephant densities.

South Africa's elephants are kept in fenced-off protected areas, which necessitates intensive management strategies. There are high levels of concern about how elephants influence vegetation and habitats. This explains the demand for increased research and resulting publications in South Africa. Another factor that could explain why South Africa has the highest number of studies could be that it is the most developed third world country on the continent, compared to for example Botswana. The presence and number of academic institutions, collaborative opportunities, and access to research funding, developed and maintained infrastructure, and a large number of protected areas and national parks all contribute towards the number of publications from the country.

Botswana has an estimated 131 626 number of elephants in an area covering approximately 228 073 km^2. South Africa is home to approximately 18 841 elephants in a 30 651 km^2 area (Thouless et al., 2016). The estimated density of elephants equates to 0.6 individual animals per square kilometer (0.6 /km^2) for both countries.

Field-based methods

Field-based methods have been used for many decades in ecological studies. Using field-based methods, information about the extent, spatial variation and resources species preferences by elephants can be studied in detail. Such information is essential for the development of effective management plans for conservation and protected areas. Although FB studies can be impractical and costly when applied in large areas and when large-scale datasets are required on a regular basis, they provide detailed ecological data at smaller scales and need to be simple enough to be widely applied in protected areas with limited capacity (Simms, 2009; Buchanan et al., 2013).

The highest number of studies on African elephants and their influence on vegetation using field-based methods emanated from southern Africa (*Table 2*). Almost half (48%) of the field-based studies are from South Africa, 32% from Zimbabwe and 16% from Botswana. Although Botswana and adjacent areas have the largest population of elephants in the world (Skarpe et al., 2004), only ten field-based studies on the impact of elephants on vegetation are from Botswana. South Africa and Zimbabwe are the most active countries regarding research on the interaction between elephants and plants, with 30 and 20 field-based studies, respectively (*Table 2*). The majority of reviewed studies located in South Africa were done in the Kruger National Park (43%, n = 13) and ten percent each (n = 3) were done for both Venetia-Limpopo Nature Reserve and Addo-Elephant National Park. All field-based studies in Botswana were conducted in the Northern-Botswana area along the Chobe River and Okavango Delta.

The lead and last authors for the field-based methods have affiliations with institutions in South Africa (26%), the US (17%) and the UK (10%). This shows that a significant proportion of field-based research on the impact of elephants is affiliated to Africa, while the US and UK researchers show active involvement.

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Remote sensing-based methods

Remote sensing techniques are cost-effective for application in large areas for collecting large-scale datasets (Duro et al., 2007). Limitations relate to limited funding to acquire satellite images, facilities, accessibility to data and the skills required to manage such datasets.

Botswana applies remotely sensed data more actively than all other countries in the sub-Saharan region (*Table 2*). In southern Africa, five out of 13 studies (38%) who used remotely sensed data were from Botswana, three (23%) were from South Africa, two (15%) from Zimbabwe and one (8%) from Zambia. Only one study per country in East Africa (Kenya and Uganda) used remotely sensed data, while there were no such studies from central and West African countries. Thouless et al. (2016) highlight factors that contribute to the accuracy of elephant densities in different countries, which may also influence the probabilities of executing remote-sensing research studies. Some countries may not have the financial means and expertise to conduct systematic elephant censuses on a regular basis, while countries that have political conflicts may not have the time or finances to do these surveys, let alone research.

Multispectral images such as Landsat and SPOT images, Aerial photographs, MODIS and Normalised Difference Vegetation Index (NDVI) were used in 13 remote sensing-based studies. Three of these studies were done in South Africa and were based in the Kruger National Park. One of them used panchromatic aerial photographs and digital SPOT imagery (Munyati and Sinthumule, 2016), while the other two used state of the art hyperspectral satellite imagery to capture the three-dimensional (3D) structure of vegetation (Asner et al., 2009; Levick et al., 2009). Both of the studies used LiDAR imagery to study the large-scale impact of herbivory on the structural diversity of vegetation. Levick et al. (2009) also highlight the value of 3D remote sensing in the assessment of conservation management outcomes.

The lead and last authors for remote sensing-based methods are mostly affiliated with institutions in the USA (6%), followed by Botswana, South Africa and the UK with 2% each. The low number of lead and last authors with affiliations in Africa may suggest that foreign institutions have financed the research conducted in Africa. Alternatively, this could relate to a slow transfer pace of technology and skills by developed countries to developing countries.

Publishing scientific journals

From the 43 scientific journals (*Table 4*) that published the reviewed studies in this paper, 84% (n = 36) were from outside the African continent, and only 15% (n = 7) were in journals from within Africa. The 14 studies that used remote-sensing data were published in journals outside the African continent, while 22 of the field-based studies were in African journals and 70 in journals outside Africa. The Journal of Tropical Ecology (United States of America – USA) published the highest number of studies (n = 13) followed by the African Journal of Ecology (England) publishing eleven. Within Africa, 19 of the field-based studies were published in five South African journals (Koedoe, SA Journal of Botany, SA Journal of Science, SA Journal of Wildlife Research and the Transactions of the Royal Society of South Africa), two studies in a Kenyan journal, Pachyderm and one in a Zimbabwean journal, Kirkia. No remote sensing studies were published in any of the African journals. The South African

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Journal of Wildlife Research published the majority of the South African studies (n = 7) followed by Koedoe (n = 6).

Elephants are major agents of change to woody vegetation as observed in some studies (Anderson and Walker, 1974; Caughley, 1976; Guy, 1976). Despite elephants modifying woody vegetation, Thomson (1992) alluded that no protected area in Africa is big enough to maintain elephants in a healthy state indefinitely without population management manipulation. Culling elephants, as a means of preventing woody vegetation loss is unlikely to produce the desired effects (Ben-Shahar, 1996a) since there is adequate production of browse available for elephants in drought years. The use of contraceptives is impractical for elephant cows due to the requirement for frequent follow-up treatments. Contraceptives are expensive to administer for both elephant cows and bulls. As our protected areas become overpopulated with increasing numbers of elephants, three things are bound to happen: (i) destruction of woodlands that will be replaced by mixed scrubland/grassland or degraded savanna; (ii) a catastrophic crash of elephant populations; and (iii) loss of plants and animals (Thomson, 1992).

Collecting ecological data on a regular basis from large, inaccessible and often dangerous areas (due to the presence of lion, leopard, rhinoceros, buffalo and elephant) using field-based methods can be challenging. Limitations relate to accessing rugged terrain, large areas to traverse, time constraints and financial implications. Using remote sensing techniques integrated with traditional field-based approaches, we can identify the biophysical characteristics of landscapes, predict species distributions, determine spatial variability in species richness, and monitor the impact of species on their environment (Kerr and Ostrovsky, 2003; Kohi et al., 2010) with less time spent in the field. Limitations of remote sensing techniques include the need to be integrated with field-based observations to validate results (Reinke et al., 2006). Collecting remotely sensed data could be very costly, with limited access in some instances. It is crucial to identify appropriate imaging characteristics (such as spatial and spectral resolution) suitable for processing and extracting relevant and vital information (Adam et al., 2010). Garrity et al. (2013) identified a shortcoming in detecting trees that are in various stages of morbidity due to the limited availability of archived satellite imagery. Regardless of the recognized limitations to using remotely sensed data, it is still a valuable tool that continues to prove its potential for use in a wide range of vegetation studies providing timely, up-to-date and accurate information for sustainable and effective management of vegetation (Adam et al., 2010).

We have noted the lack of available published studies on the use of remotely sensed data to map the small-scale impact of African elephant on woody vegetation. Only two reviewed studies used hyperspectral images to determine the large-scale responses of vegetation and ecosystem structure to the presence/absence of herbivory (Asner et al., 2009) and to gain insight into the influence of fire and herbivory to the structure and heterogeneity of savanna vegetation (Levick et al., 2009). Northern Botswana is known to have the highest density of elephants in the world (Skarpe et al., 2004) and the majority of studies from Botswana reported that elephant damage to vegetation is not significant. As noted by Ben-Shahar (1996b), the impact of elephants is generally distributed randomly. Some authors used field-based methods to study the effects of elephants on woodland modification and the implications this has on the diversity of bird species (Herremans, 1995) and the nesting sites of Southern Ground Hornbill (Henley and Henley, 2005). The placement of artificial water points influences tree biomass (Ben-Shahar, 1996a) and structure (Kalwij et al., 2010). Tall tree densities are

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affected by elephants in mopane woodlands (Ben-Shahar, 1998). From these studies, the impact of elephants was not significant, and in other instances, woody biomass and densities remained unchanged, except for new damage to vegetation during the dry season, which was recorded by Ben Shahar (1996b).

Conclusion

Field-based methods have been extensively used in ecology since the 1960s and are still effectively used. From reviewed studies on the impact of elephants on woody vegetation that applied field-based methods, we have noticed a steady increase from an average of two studies per year before the 20th century, to an average of four studies after the 20th century. These methods provide detailed and reliable datasets. This is an indication that field-based methods are still relevant today, even with advancements in technology in the form of remote sensing techniques.

Remote sensing and GPS technology have also been utilized to track elephant movements (Kahumbu, 2002; Bohrer et al., 2014; Xu et al., 2017). Field-based methods are utilized in combination with remote sensing techniques for field observations. Although remote sensing techniques offer cost-effective and repeatable ways for regular data collection and monitoring for trends, there is also a fieldwork element associated with it. However, using remote sensing techniques, time and labour required for field surveys, especially on an annual basis, are drastically reduced (Jensen, 2005). The results of our reviews indicate that there is a limited amount of studies that used remote sensing-based methods for studying the impact of elephants on woody vegetation. Even the available studies are sparsely distributed between 1997 and 2017, with three studies published in 2009, two of which were done in the Kruger National Park, South Africa and one in Hwange National Park, Zimbabwe.

Guldemond et al. (2017) call for the management of habitats used by elephants to maintain the heterogeneity of Savanna, with particular attention to important tree species of conservation value. These can only be achieved with improved and efficient methods of data collection. Remote sensing techniques can be useful and practical and should be used in conjunction with field-based methods for improved data collection, analyses and interpretation. However, there is a need for the transfer of technology and skills, capacity building and increased support to Africa. Access to quality remotely sensed data needs to be improved to promote the use of this technology and its integration into nature conservation disciplines to address conservation research questions about vegetation trends and responses to impact. Collaborative projects between skilled remote-sensing and field-based researchers are recommended to increase research capacity and the use of technology.

Based on the studies we reviewed our conclusions suggest that the use of remote sensing techniques in studying the impact of elephants on woody vegetation are currently limited. The limited number of studies that applied remote sensing-based methods are in Africa. We therefore encourage the integration of data collected from both remote sensing technology and field-based methods for monitoring the influence of elephants on woody vegetation. Remote sensing techniques are continuously improving and incorporating data collected with the latest technology will enhance habitat management strategies in the future. It is important to highlight that most African countries are in a developmental stage with limited resources and capacity. We also recommend that researchers should take advantage of available novel tools such as

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remote sensing technology to explore its practical and cost-effective applications to managing environments containing elephants, especially in a world that is becoming tech-savvy.

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APPENDIX A

A list of peer-reviewed studies published between 1970 and 2017

Studies that used remote sensing-based methods:

[1] Asner, G. P., Levick, S. R., Kennedy-Bowdoin, T., Knapp, D. E., Emerson, R., Jacobson, J., Colgan, M. S., Martin, R. E. (2009): Large-scale impacts of herbivores on the structural diversity of African savannas. – Proceedings of the National Academy of Sciences 106(12): 4947-4952.

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Studies that used field-based methods:

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APPENDIX B

	Region	**Country**	**Number of elephants**
1	Southern Africa	Botswana	131 626
2	Southern Africa	Zimbabwe	82 630
3	East Africa	Tanzania	50 433
4	East Africa	Kenya	22 809
5	Southern Africa	Namibia	22 754
6	Southern Africa	Zambia	21 967
7	Southern Africa	South Africa	18 841
8	Southern Africa	Mozambique	10 884
9	East Africa	South Sudan	7 103
10	Central Africa	Gabon	7 058
11	West Africa	Burkina Faso	6 850
12	Central Africa	Cameroon	6 830
13	Central Africa	Congo	6 057
14	East Africa	Uganda	4 923
15	Southern Africa	Angola	3 396
16	West Africa	Benin	2 984
17	Central Africa	DRC	1 794
18	Southern Africa	Malawi	1 307
19	East Africa	Etiophia	1 017
20	West Africa	Ghana	994
21	Central Africa	Equatorial Guinea	884
22	Central Africa	Chad	794
23	Central Africa	Central African Republic	702
24	West Africa	Mali	253
25	West Africa	Cote D'ivoire	189
26	West Africa	Liberia	124
27	West Africa	Nigeria	94
28	East Africa	Rwanda	88
29	Southern Africa	Swaziland	42
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