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Climate Change and Anthropogenic Factors Are Influencing the Loss of Habitats and Emerging Human–Elephant Conflict in the Namib Desert

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Abstract: Climate change and anthropogenic factors' impact on habitat loss is a growing problem that is influencing unsustainable wildlife local-population home range shifts and triggering an increase in human–wildlife conflict (HWC). Yet, keystone species involved in HWC such as elephants play a vital role in nature-based ecosystem services and have important economic and cultural value to the people that are living with them. To understand how climate change and anthropogenic factors affect habitat loss and elephants' home range shift, the movement of Namib desert-dwelling elephants was monitored and observed in the Ugab River basin between February 2018 and November 2020 at fortnight intervals. There are 87 elephants in the Ugab River basin that are distributed into two subpopulations: desert-dwelling elephants (N = 28) and semi-desert-dwelling elephants (N = 59). To achieve the objective of the study, land cover change, elephant movement, rainfall, and temperature data were analysed using ArcGIS spatial and statistical tools, such as image analysis, optimised hot spot analysis (OHSA), and cost distance analysis, to distinguish habitat vegetation changes and home range shifts and how these link to emerging human–elephant conflict (HEC) hot spots. Human farming activities, poor rainfall, and frequent droughts are responsible for the loss of habitat of around 73.0% in the lower catchment of the ephemeral river streams; therefore, the urgency of conserving and sustaining these habitats and desert-dwelling elephants is discussed here.

Keywords: desert-dwelling elephants; home range shift; habitat loss; Namib Desert; ephemeral rivers; vegetation cover; NDVI; human–elephant conflict

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1. Introduction

The overall African elephant population continues to decrease, which might leave one of the world's most charismatic species in jeopardy of extinction [1]. The literature indicated that habitat loss and fragmentation, poaching for ivory, and human–elephant conflict (HEC) are among the most researched factors contributing to the elephant population's decline [2–4]. It is further established that the impacts of human activities [5,6] and climate change undoubtedly lead to habitat and biodiversity loss [7–9]. Targets to limit extinction are not easily achievable [10], affecting species and habitats at local and regional scales [11–13], such as desert-dwelling elephants and their habitats in the Namib Desert. Recently, these worrying observations have led to the reclassification of the African savanna elephant (*Loxodonta africana*) and the forest elephant (*L. cyclotis*) from vulnerable to endangered and critically endangered, respectively, by the IUCN [14–16]. Yet, this keystone species plays a vital role in nature-based ecosystem services and has important economic and cultural value to human populations [17].

The world population of elephants was estimated to be over 1.3 million in 1979 [18], but it has drastically decreased over the last four decades, as some local and regional populations have declined significantly. By 2007, the elephant population in Africa was estimated at 470,000 to 690,000 [19]. A further decline of 144,000 elephants was recorded in 2014, and the population has continued to decline at an unprecedented rate every year [4]. Until 2021, there were approximately 415,400 elephants (*L. africana* and *L. cyclotis)* in Africa [20,21], but population estimates can be questionable, and the number of elephants roaming the African continent may be smaller than that presented in many studies. Data from the Great Elephant Census (GEC) indicate that only 16.0% of the surveyed African savanna elephants roam out of protected areas. However, these areas represent 80.0% of the elephant distribution range in Africa [22]. Thus, most of the elephant's distribution area does not have formal protection, and they are more exposed to the possibility of losing major habitats.

Namibia is one of the countries with a high population of free-roaming elephants outside of national parks. The Ministry of Environment and Tourism (MEFT) reports that 31.0% of 23,736 elephants in Namibia roam outside protected areas [23]. In the 1900s, these elephants had a known home range—an area over which an animal (or group of animals) regularly lives and traverses in its normal activities—of 22.1% (calculated from the report of De Villiers (1975), as cited in MEFT (2021) [23], and they may have had a distribution area—a geographical area where a species can be found—greater than 56.0% of the country's total area of 823,000 km^2 (Supplementary Figure S1). However, this area declined to 13.7% by the 1990s before increasing again to 21.3% in 2020. Nevertheless, not all local populations are growing despite the elephant's national population growth, especially in the northwest part of the Namib Desert, where fragmented local populations within ephemeral river basins, including the Ugab River basin, are reported to be declining [24,25].

1.1. The Desert Elephants

Namib Desert elephants were once close to extinction, and their population has been classified as local and restored since the early 1980s [23]. A genetic distinctiveness between these elephants and other populations of *L. africana* has not yet been established, and studies indicate that what enabled them to survive in the extremely arid environment of the desert was their high learning capacity and adaptive behaviour [26,27]. Thus, they are an ecotype instead of a different species.

This ecotype is divided into two subpopulations: desert-dwelling elephants and semi-desert-dwelling elephants; both are widely distributed throughout communal land and community conservancy. Desert-dwelling elephants roam freely within the ephemeral river basins of the Erongo and Kunene regions (the latter is in the northwest of the country and partially hosts our study area) and can be found below the 200 mm isohyet of each basin [28–31]. More specifically, the herds of this population include less than 250 elephants and are found at the lower catchments of major basins of the Ugab, Huab, Hoanib, Hoarusib, and Uniab Rivers. The adjacent populations of over 200 elephants found further inland in the semi-arid savanna grasslands at the upper catchments of the Ugab and Huab River Basins are classified as transitional or semi-desert elephant populations [23,32]. Namib Desert is characterised by frequent severe droughts, especially in the last 10 years [33], and an increase in the average maximum temperature recorded during the hot months from October to January [34,35], potentially making the Namib Desert one of the harsh environments home to the largest land mammals that may become inhabitable in the near future.

1.2. Namibia as One of the Most Vulnerable Countries to Climate Change and HWC

Namibia is classified as being among the most vulnerable countries relative to climate change, and it is characterised by reduced rainfall; a rapid increase in the number of consecutive dry days, flash floods (Table S1), and frequent droughts; and high-temperature increases [13,36–39], a situation predicted to be getting worse for tropical regions in a recent IPCC Assessment Report (AR6) [40]. The country has an average annual rainfall of 340 mm, with these values ranging from 0 mm (for example, in the western desert) to over than 600 mm (as in the northeast savanna woodland ecosystem) [41].

Namibia is projected to experience a radical temperature increase of 1.0 °C to 3.5 °C in the summer and 1.0 °C to 4.0 °C in the winter by 2050–2065 [34,38,39], further contributing to evaporation that is already exceeding annual rainfall [34]. Moreover, only 1.0% of the annual rainfall infiltrates to recharge the underground aquifers [38], but the communal farms present in the regions of ephemeral rivers (as with the Ugab River communal farms) depend mostly on borehole water throughout the year [23]. Farmers with limited income rely more on few natural springs for human and livestock water consumption [42], in addition to these springs being the main water source for wildlife. Furthermore, the temperature increase is projected to negatively affect ecosystems and local populations of endemic species, possibly leading to their extinction [13].

The observed trends from the World Bank Group country's climate portal [43] show an increase in the annual maximum mean temperature (AMaMT) (Figure 1A), a moderate rise in the annual mean temperature (AMT) (Figure 1B), and a rapid increase in the observed number of consecutive dry days (CDD) (Table S2) over the past 30 years [44]. The 95-confidence interval equation line referring to the average of the national annual precipitation (NAP) (Figure 1C) and the Kunene region annual precipitation (KAP) (Figure 1D), over this time interval, tends towards values indicating a slight increase in annual mean rainfall. However, a loess line with a 95-confidence interval displays an average decrease in NAP since 2008 and in KAP since 2006 (Figure 1E,F).

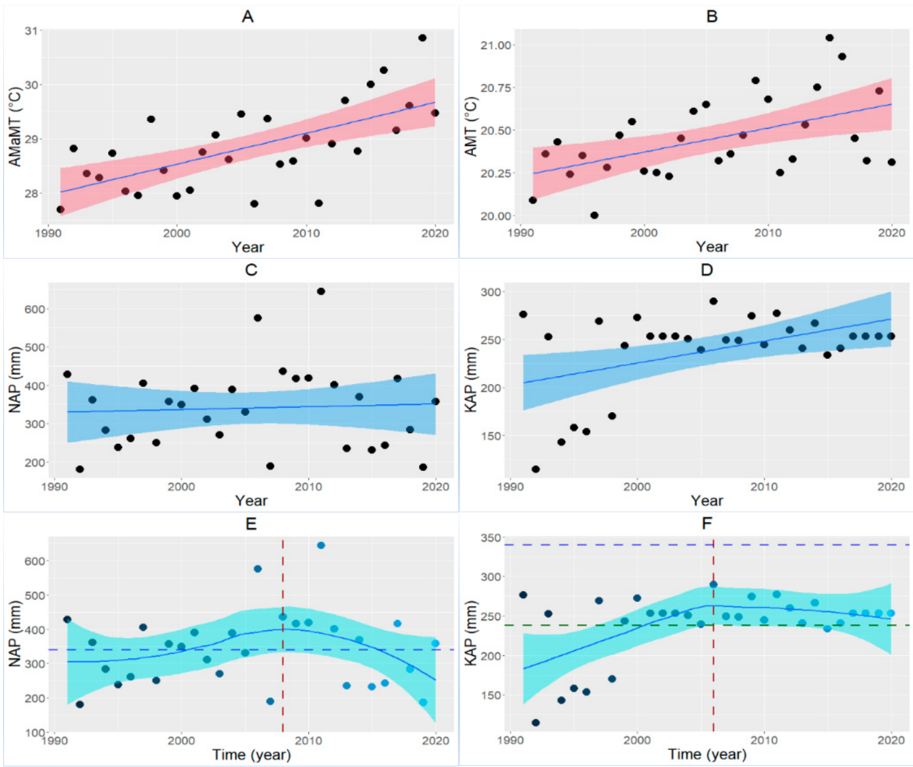

Figure 1. Climate data observation in Namibia over 30 years. Figure shows linear model trend lines for the annual maximum mean temperature (AMaMT) in °C (**A**), the annual mean temperature (AMT) (**B**), the average of the national annual precipitation (NAP) (**C**), and the average of the Kunene region annual precipitation (KAP) (**D**). The average observed precipitation between 1991 and 2020 regarding to the NAP (**E**) and KAP (**F**) data is indicated by the blue and green dashed abline, respectively, whereas the red dashed abline indicates the highest average observation point. Figure is constructed with the climate data in Table S2, adapted with permission from the World Bank Group Climate Change Knowledge Portal (CCKP) (2022, the World Bank Group) [43], using a an Open Access ggplot2 V3.4.2 R package by Wickham (2016) (Accessed from: https://ggplot2.tidyverse.org, accessed on 20 April 2023) [45] in R 4.3.0 Open Access software (accessed from: https://www.r-project.org/, accessed on 20 April 2023) [46].

As the arid transitional areas are more vulnerable to climate change [40], and Namibia's human population is widely scattered in these rural areas—for example, in 2011, more than half of the national population was dispersed in these areas, and almost 75.0% of the inhabitants of the Kunene region are within rural areas—the people and wildlife of Namibia may be facing an unprecedented challenge with advancing climate change. As competition for resources intensify, the interaction between people and wildlife across the landscape is believed to increase HWC [47]. Uncontrolled livestock herds grazing on unfenced land led to an overlap of livestock grazing land and wildlife home ranges [48], but the problem does not end there. Human settlement growth and increasing farmland are leading to deforestation and desertification [49–51], threatening vulnerable ecosystems and biodiversity [13,38,39].

The government encourages communal farmers to register unoccupied land as community conservation units to care for wildlife [52]. In addition, the government and non-governmental organisations (NGOs) develop strategies to empower the residents on how to coexist with wildlife [48,52–54]. Still, the efforts seem not to be enough, with HWC increasing [55] and expanding into new areas [23].

1.3. Namib Desert Ephemeral Rivers and Aims of the Study

The ephemeral rivers of the Namib Desert cut through igneous rocks [56] and may flow for a few days during the summer across this desert [57]. They are mainly dominated by *Faidherbia albida*, *Vachellia erioloba*, and *V. karroo* trees (previously belonging to the genus *Acacia*) and *Salvadora persica* bushes [58–62]. A high abundance of *Phragmites australis* and *Tamarix usneoides* were also observed at natural springs within the riverbed. The importance of these habitats should not be underestimated, as a few perennial springs in ephemeral desert river catchments are the primary source of water for wildlife and riparian vegetation, and both domestic and wildlife animals depend on this vegetation. For example, riparian forests on the riverbanks are essential for elephants, attracting them during dry seasons for food and shade (shelter) [30,63].

Findings outlined by previous studies conducted on dry lands and ephemeral rivers of the Namib Desert on drivers of underground water decline [64] and observations of large trees die-off [61,62,65] supported the development of the objectives of this study. This work established that climate change indicators (such as temperature rise, frequent droughts, and decreasing rainfall [40,66]) and anthropogenic factors (such as overgrazing and over-abstraction of groundwater [57]) negatively affect desert habitats and the availability of vegetation, and such changes are leading to altered elephant behaviour and risks to their ability to survive in this region.

The general aims of this study were to analyse the potential threats to desert-dwelling elephants' habitats, especially climate change and anthropogenic factors, and to understand how these threats influence elephant home range shifts. Spatiotemporal analysis of elephant movement was used to track home range shift patterns, helping to understand what is causing this, where elephants are going, and how such events might impact human populations and, consequently, the elephants themselves.

2. Methods

2.1. Study Area

The study area is in the northwest part of the country, where the Ugab River basin (Figure 2A) is located, and where the maximum temperature exceeds 40 °C in the summer [29]. The Ugab River is one of the ephemeral rivers present in the interior of Namibia that characterises the country's aridness [67]; it has a catchment area of 28,000 km^2, a length of over 540.0 km, and it flows east-to-west into the Atlantic Ocean. There are no perennial rivers in this region [67], and the situation of Namibia's arid landscapes, which already lack surface water during the dry season [57], is worsening with advancing climate change. Consequently, pressures on these ecosystems increase, as do concerns about the future of wildlife and human livelihoods [44,68]. The Ugab River desert-dwelling elephants historically roamed within the lower catchment, between 20.6°–21.1° S and 13.9°–15.2° E. Therefore, the previously known home range for the population was demarcated based on descriptive and observational studies [27–31,63,69] so that it could later be compared with the home range observed in this study.

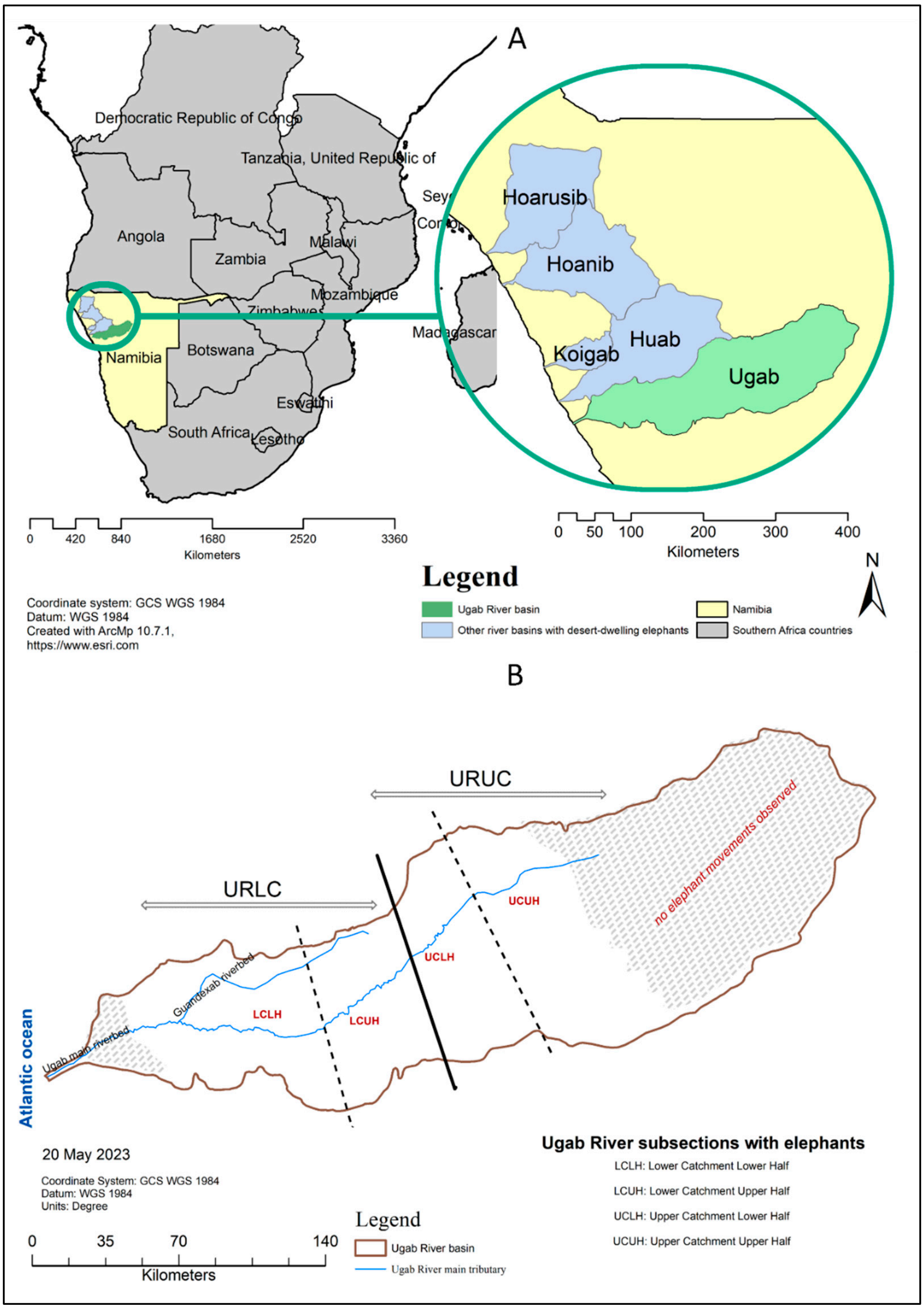

Figure 2. (**A**) Location of the Namib Desert major ephemeral rivers inhabited by elephants in northwest Namibia. (**B**) Division of Ugab River basin into the Ugab River Lower Catchment (URLC)—subdivided into Lower Catchment Lower Half (LCLH) and Lower Catchment Upper Half (LCUH)—and the Ugab River Upper Catchment (URUC)—subdivided into Upper Catchment Lower Half (UCLH) and Upper Catchment Upper Half (UCUH). The border and watershed shapefiles used to construct the figure were obtained from the Ministry of Agriculture, Water and Land Reform, Luther Street, Windhoek, Namibia (2022).

Given the isolation of the two populations in the past, the Ugab River basin was divided into two sections: the Ugab River Lower Catchment (URLC) and the Ugab River Upper Catchment (URUC) (Figure 2B). The URLC was further subdivided into two sections, the Lower Catchment Lower Half (LCLH) and the Lower Catchment Upper Half (LCUH). The two sections of the URLC are the historic home range for the desert-dwelling elephants, with the LCLH representing the area mainly used in the winter and the LCUH in the summer [28,58,60,70]. The URUC was split into the Upper Catchment Lower Half (UCLH) and the Upper Catchment Upper Half (UCUH). The URUC represents the historic home range of the semi-desert elephant population. The two populations' home ranges have not been overlapping in the past based on information obtained through ad hoc interviews on historical observations made by farmers, researchers, and local conservation institutions.

2.2. Data Collection

2.2.1. Elephant Observation Movements and Population Structure

The data used in this study were collected in the field and from open-source databases and previous studies. Data from other studies are presented as part of analytical methods and include vegetation raster, rainfall, temperature, historical movement, and home range data. Regarding the latter, it was considered from the information present in Brown et al. (2020), Enzerink and Liefferink (2017), Garstang et al. (2014), Ishida et al. (2016), MEFT (2007, 2020, 2021), Viljoen (1987, 1989a, 1989b), and Viljoen and Bothma (1990) [23,25,27–29,31,47,63,69,71,72]. Additional data from other sources were used: Landsat satellite images (United States Geological Survey) [73], precipitation (World Bank Group) [43], records of drought events cited in Hitila (2019), the Office of Prime Minister's Directorate of Disaster Risk Management (2021), and the Cooperation in International Waters in Africa (CIWA) (2021) that make use of the Emergency Events Database (EM-DAT), Thomson (2021) [33,68,74,75].

Between February 2018 and September 2020, 28 elephants in the URLC (3 herds and 3 breeding males) and 59 in the URUC (3 herds and 7 breeding males) were observed at fortnight intervals. By the end of data collection, 5 and 7 of these individuals, respectively, had died. Daily tracking was conducted from 08h00 to 18h00 by foot and car. The elephants were not collared during the project, requiring careful tracking along small trails between farms (usually 3.0 to 5.0 km apart). Other field observations (such as assessing boreholes conditions and talking to farmers) were carried out until November 2020.

The guidelines of Princeton University [76] on identifying and ageing animals' markings by animal tracking were adopted and modified. An elephant tracking chart was developed covering topics such as the ageing of elephants' footprints and dung, the softness of leaves fed and dropped on the ground, and the classification of individual imprints. Data collectors aged elephant dung as: recent, if it was less than 3 h old (occurred during the day) or 8 h old (from the previous night); not so recent, if it was between 1 to 2 days; and old, if it was between 3 to 5 days. These data were important to ascertain what was the tracking time required to find the herd or individual males.

Even though savanna elephant dung has been fairly studied by many researchers, such as Nchanji and Plumptre (2001) and Barnes et al. (1997) [77,78], the studies did not focus on dung ageing for elephants tracking purposes. However, Masunga et al. (2006) [79] presented an important perspective, mentioning how dung ageing monitoring gaps vary widely and discussing the role of moisture, shade from trees, and the season in the dung decay time-frame. The study presented here also used dung colour to age elephant dung. The researchers relied on their own tracking knowledge of elephants and other species supplemented with information from the literature to generate their own elephant dung ageing chart. A dung was identified as recent if it was wet on the surface and varied in colour from light to dark green (depending on the colour of the plant the elephant ate, which varies with the seasons)—information supported by 40 years of experience tracking elephants and other mammals in the Namib Desert of Mattias Kangumbe (27 February 2018, personal communication).

Leaves that fell on the ground while the elephants were feeding were used to age elephant tracks. For this, it was important to consider the influence of weather conditions on the ageing rate. Leaves get drier as they age but can remain fresh for up to 24 h if it rains, is cloudy or humid, or when it is cold in the winter. In addition, ageing also depends on the plant species, with the leaves of succulent plants staying wet longer than plants with thinner, softer leaves.

To avoid disturbance by invading vehicles, and considering that herds and individual males have shown different levels of tolerance to human presence depending on distance, non-invasive methods and distance restrictions were set up based on animals' behaviours and reactions. Desert-dwelling elephants were not shy as semi-desert-dwelling elephants since data collectors could approach the animals closer without elephants showing signs of being disturbed. Therefore, we maintained a minimum 50 m distance if desert-dwelling elephants were relaxed and a 100 m distance if they were not. When approaching the elephants at the URUC, researchers maintained a 100 m minimum distance when the animals were relaxed (except when feeding in bushy areas) and 150 m if not settled.

When an individual male or a herd was found, the location coordinates were recorded. Individual elephants were counted in every herd spotted, and the elephants' ages were estimated following existing methods [80,81]. The physical characteristics of individuals (males or members of a herd) were identified at every new sighting location, as described in Viljoen (1989) [28], adopted from Douglas–Hamilton (1972) [82]. The data recorded for each individual were sex, age, and behaviour, and, in the case of herds, the number of adults and the total number of elephants that constituted them were also recorded [71,83]. Identification of matriarchs and relationships between calves, juveniles, and adult cows was carried out carefully, following Elephant Voices guidelines [83]. Each individual and each herd were assigned a unique code (e.g., ULH1 for Ugab River Lower Catchment Herd 1 and UUH1 for Ugab River Upper Catchment Herd 1) for future reference and identification.

The previous photographs taken of the elephants, in parallel with the information presented in the guidelines [83] and in an unpublished report from 2019 [84], to verify if a certain individual (or herd) was known or not. For cases where it was the first time that the elephant was sighted, a new individual identification code was created. Specific details such as cuts in ears and tusk shapes helped to identify individuals, which made it possible to know which elephants were found dead, broke facilities at a farm, or gave birth. Elephant sightings were recorded more than once a day if the same individual or herd changed the position for a distance longer than three km from the previous sighting site. This record made it possible to know the direction in which the individual/herd was going, also facilitating its observation and tracking in the next day.

2.2.2. Human–Elephant Conflict Events

Human–elephant conflict (HEC) events, such as damage to water infrastructure, were recorded through ad hoc interviews with farmers and community leaders. In order to guarantee the veracity of the information provided, the project data collector always observed the damage to the infrastructure accompanied by the farmers. Elephant sightings and conflict events were also reported via phone calls. However, mobile cell phone network limitations, together with COVID-19 restrictions implemented at the time of the collection of this data, affected visits to farms and communication with the people involved, and may have led to limitations in the collected data.

The coordinates of the locations of the events (also referred here as HEC hot spots) were recorded on-site and through ArcGIS 10.7.1 software. Records included the types of infrastructure damaged and the frequency of elephant visits to the farm or water point (monthly, weekly, or seasonally). For reasons of animal safety and the ongoing fieldwork, the coordinates and physical description of the sites will not be provided in the attached supplementary materials (Table S3).

2.3. Data Analysis

2.3.1. Spatiotemporal Analysis of Elephant Movement Data to Trace Home Range Shift Patterns

The weighted optimised hot spot analysis (OHSA) tool of ArcMap 10.7.1 was used to map the desert-dwelling elephant distribution shift and HEC hot spots based on the number of sightings observed within specific areas. Hot spot analysis is widely used in many research areas to assist in identifying areas of interest (e.g., fire management areas [85]), but it can also be applied in the study of spatial sciences and ecology [86]. The tool identifies and cluster statistically significant high values (hot spots) and low values (cold spots) [87], using an input feature class that contains data points at a 95.0% confidence level (p = 0.05) at Gi_Bin cluster levels of +3 and −3 (ESRI https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/optimized-hot-spot-analysis.htm, accessed on 1 February 2021). Input data must meet OHSA requirements, i.e., data have to be spatially autocorrelated (and not randomly occurring), and consideration must be given to an appropriate projection and screening for outliers (an observation that lies an abnormal distance from other values) and any missing values. The spatial autocorrelation of the data was measured using Moran's Index, and it obtained a p-value < 0.01, indicating that the values in the dataset tended to cluster.

The OHSA tool filtered the data and excluded outliers from the analysis. Thus, this tool was initially used to identify the core distribution areas of the populations, and then the kernel density tool could be used to map and visualize the seasonal distribution density of the elephant population and HEC hot spots.

Finally, 30.0 km buffer of all sightings of males and herds from each catchment section were created to calculate the population's home range. The use of buffers to study animal movement and distribution has been used before to answer questions of interest about species [88], and the radius size of a buffer can vary between study areas, depending on climate and types of vegetation and habitat [89]. The 30.0 km buffers were used to estimate a potential distance to waterpoints, and the choice of this value was made considering the midpoint of the values presented in Viljoen (1989) [28], which indicated that elephants in the Namib Desert could travel far from waterpoints in the dry season in a range of 20.0–40.0 km/day. For data analysis, it was important to consider that the daily distance covered by elephants was greater in the desert than in wetter areas [90], even though the main area used (core area) in this arid habitat was usually smaller. Random visits to farms and settlements within the 30.0 km buffer also allowed us to gather information about the presence of elephants in villages and water points. Subsequently, to identify newly established home range and habitats, the data collected in this study were compared with data presented by Viljoen (1989) [28], referring to elephants in the distribution range below the 200 mm isohyet. Random visits to farms and settlements within the 30.0 km buffer also allowed us to gather information about the presence of elephants in villages and water points.

2.3.2. Identification of Historic Vegetation Cover Change and Habitat Modification

Vegetation health was analysed within the historic home range of desert-dwelling elephants at LCLH. The area included natural springs, *F. albida* trees, and several bush species. The vegetation at this site was mainly found in and near the riverbed, and there were patches of dead trees within the riverine, covering areas larger than 500 × 500 m. Therefore, it was intended to determine whether tree mortality was being influenced by the severe drought events and reduced rainfall in the region (Table S1) [33–35].

The use of multispectral satellite imagery bands from Landsat 7 and 8, accessed through the United States Geological Survey Earth Explorer (USGS https://earthexplorer.usgs.gov/, accessed on 1 February 2021), made it possible to examine vegetation cover and its health. The analysed vegetation images came from a location whose coordinates were 20.9°–20.9° S and 14.4°–14.7° E and had a length of 38.5 km, 1.0 km at the widest point, and an area of 164.5 km^2. The best images (those with less than 5.0% cloud cover) were downloaded separately for the wet seasons of 2000, 2006, 2010, 2015, and 2020. Afterwards, these images were inspected again (to look in more detail at cloud cover and dust), projected to the WGS_1984_UTM_Zone_33N, and merged using the mosaic raster function [91]. To render these raster datasets together, the bands 1–7 for Landsat 7 Enhanced Thematic Mapper (ETM+) and 1–8 for the Landsat 8 Operational Land Imager (OLI) were composted to form a single raster image for each year [91,92], using the ArcMap 10.7.1's Image Analysis Raster Composite tool. Bands combinations of 4, 3, and 2 and 5, 4, and 3 were selected for Landsat 7 ETM and 8 OLI surface reflectance data, respectively [93–95]. However, the OLI reflectance is greater than the ETM reflectance band, thus there could be some differences for the near-infrared (NIR) and visible light (VIS) produced [96]. The selected bands combination was suitable for classifying and quantifying vegetation and for driving the Normalised Difference Vegetation Index (NDVI), using the formula [97,98]:

$$NDVI = (NIR - VIS)/(NIR + VIS)$$

The land surface cover types were reclassified [91] to differentiate between seasonal vegetation (SVeg) cover, perennial unhealthy vegetation (PUVeg) cover, and perennial health vegetation (PHVeg) cover. An NDVI index score of zero indicated no vegetation, and the closer this value was to 1 the greater the density of green leaves [93]. Thus, vegetation with a score greater than 0.6 was considered healthy, and the condition of vegetation was verified in the field and using the application Google Earth Pro (for example, through the observation of cells coming from fully green or trees in bad condition). Other classes, such as bare sandy areas, rocky plains, mountainous areas, and human infrastructure (mainly small, corrugated iron houses), were difficult to differentiate, especially due to the homogeneity of the colours of the rocky areas. Therefore, these classes were reclassified into two categories: rocky and bare plains and mountainous areas, which were not reported in this study but contributed to the area calculation. Furthermore, the raster layers of classified attributes, which included vegetation classes, were converted into vector layers to calculate the total area. The percentage of vegetation cover (Table S5) was calculated from these data, using ArcGIS 10.7.1 raster geometry and calculator function. Finally, a linear estimation of the missing values of the years that were not calculated was carried out using a combination of the "mutate" and "na.approx" functions of the Dplyr (https://www.rdocumentation.org/packages/dplyr/versions/1.0.10/topics/mutate) and Zoo (https://www.rdocumentation.org/packages/zoo/versions/1.8-12/topics/na.approx) packages, respectively (packages accessed on 10 February 2021).

2.3.3. Identification and Mapping of Migration Corridors

To map the commuting and migratory corridors that connected elephant habitats, a least cost method was chosen, among several modelling approaches, including factorial least-cost paths analysis, circuit theory, and the resistant kernel described in Rudnick et al. (2012) [99]. A catchment polygon was generated from an Ugab River watershed and was used as extraction extent for the images from the Landsat 8 OLI satellite. These images were taken in April 2020 and were processed for the corridor analysis. A method similar to the one declared in 2.3.2. and used in other studies [97,98] was further used to generate the vegetation index. Viljoen (1989, 1990) [28,29] pointed out that suitable vegetation and riverbeds scan attract elephants, serving as a migration corridor or as a foraging area. This information contributed to the decision of the parameters used for corridor mapping.

A signature was created to reclassify and extract vegetation with an NDVI score value above 0.6 using a table query selection in ArcMap. Considering that the high vegetation density followed river streams [29], the slope and vegetation layers (as described in Evans et al. (2020) and Hazen et al. (2021) [88,89]) and the habitat patches (generated from vegetation cover) were used to model the suitable corridors. The cells with the highest vegetation index were assigned a low value, meaning to be least cost, and the same was repeated for the elevation raster file, with the lower elevation in river streams being preferred over mountainous areas [30]. The two classified raster files were converted into an accumulative cost distance raster file (determined based on the raster cell values) using the Cost Distance tool (ESRI https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/optimized-hot-spot-analysis.htm, accessed on 30 August 2022). Another copy of a raster extraction was converted into a vector file that later served as feature polygons defining the habitat regions. This one and the cost distance file were used, as documented in the ArcGIS Pro 3.0 spatial cost connectivity tool, to generate the least cost paths. A 500 m buffer was created around the paths and then resampled with the original high-value vegetation index within the demarcated corridor buffer. The locations for the corridors were verified in the field for ground truthing purpose. Subsequently, the layers of "Habitat gain", based on observed movements, "Unoccupied Historic Habitat", and "Occupied Historic Habitat" were overlaid to create the final map.

3. Results

3.1. Elephant Movement, Home Range Shift, and Potential Emerging Human–Elephant Conflict Areas

Figure 3 shows the distribution of sightings of elephant movements from February 2018 to September 2020, made within communal conservancies (blue area) and the non-conservation regions. The average annual rainfall is indicated in mm within each home range section. This figure indicates the high prevalence of desert-dwelling elephants (in brown) in the URLC and semi-desert elephants (in blue) in the URUC. Still, the occurrence of semi-desert elephants in the lower catchment is visible, especially in the LCUH, and the presence of desert-dwelling elephants in the upper catchment, with a greater preference for the UCUH.

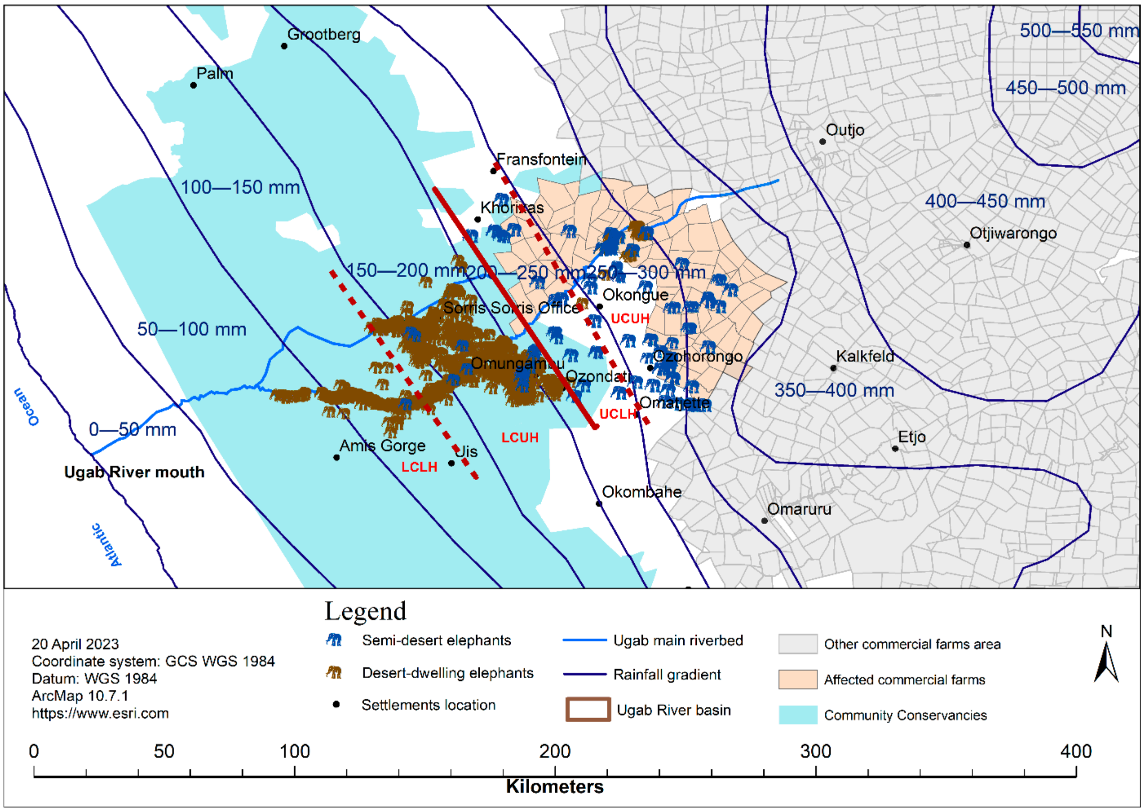

Figure 3. Distribution of elephant movement sightings from February 2018 to September 2020. A single elephant symbol refers to either an individual male, a group of males, a family group, or males and families groups. The brown symbols represent the desert-dwelling elephants, whereas the blue symbols represent the semi-desert (transitional) elephants. The land use shapefiles used to construct the figure were obtained from the Ministry of Agriculture, Water and Land Reform, Luther Street, Windhoek, Namibia (2022).

Overall, half of the sightings of elephants residing in the upper catchment home range moved within 35.0 km and 50.0 km north and south of the river, and the other half occurred within 15.0 km from the main URUC riverbed. However, sightings away from the main riverbed mostly occurred along the tributaries of the Ugab River, which runs through commercial farms in mountainous areas and rocky plains. The main range for the desert-dwelling elephants falls within community conservation areas (the light blue areas) that are managed by the residents as community conservation areas.

The Moran's I p-value < 0.01 obtained indicated that the data regarding elephants' movement were autocorrelated, and this was also confirmed by OHSA, which identified cold spots mainly in the URLC and hot spots emerging at the URUC, especially in the UCUH.

3.2. Habitats, Home Range Shift, and Potential Emerging Human–Elephant Conflict Areas

The desert-dwelling elephants have been shifting their distribution range eastward between 2018 and 2020. The overall yearly mean centre shifted by 3.8 km, between 2018 and 2019, and 60.4 km, between 2018 and 2020. Figure 4 shows that the sightings area occurred mainly along the riverbed (especially in the dry season since they move through bush and grass plains in the wet season) and that the distribution area is spreading wide-out towards the upper catchment as more major tributaries are formed. The figure demonstrates the density of desert-dwelling elephants mainly being distributed within the LCUH and LCLH in 2018 and 2019, with the latter section being more relevant during the dry season. In those years, in the wet season, elephants approached the UCLH. However, it was in 2020 that they spent a lot of time at the URUC, where they were not seen before, mostly within the UCUH from April to August. During that time, they were mainly at the commercial farms and used the UCLH section for migration between the URLC and UCUH. Most farmers located at the URUC complained that they were seeing more elephants than before, which was due to the combination of the local semi-desert elephant population and the desert-dwelling elephant population that moved into this area. As a result, damage caused by elephants at the farms increased.

The seasonal distribution of the semi-desert-dwelling elephant population (Figure 5) was mapped with the combination of sightings made in 2018, 2019, and 2020. This figure does not show data by season and year because fewer observations were recorded for this population and due to the fact that there were no major changes in annual home range. Map A indicates that elephants used the UCLH and UCUH sections during the dry season in a similar way, but, when at the UCLH, they agglomerate in the main riverbed. In the wet season, both sections of the URUC were used, but there was a tendency for elephants to concentrate in the UCUH, moving away from the main riverbed and overlapping commercial farms.

Conflict events in the lower catchment section were more frequent in areas closer to the main riverbed, and the animals seemed to spread out from it towards commercial farms in the upper catchment (Figure 6). Patterns of movement and conflict relate to the conditions of the waterpoints, i.e., the constant presence/absence of water and the accessibility to the waterpoint (both for adults and juveniles) influences the frequency it is visited (Table S3 and Supplementary Figure S2). Supplementary Figure S2 indicates the location of water points (drilled boreholes for groundwater abstraction) and the frequency with which elephants visit them (Table S3). Half of the visits recorded in the URUC occurred 15.0 km from the main riverbed, the other half 50.0 km from it, and the vast majority took place below the main riverbed (to the south). The URUC area has more accessible waterpoints, and they are being visited more frequently than those in the URLC (Supplementary Figure S2). These upper catchment waterpoints appear to be attracting more elephants, leading them to establish new habitats upstream.

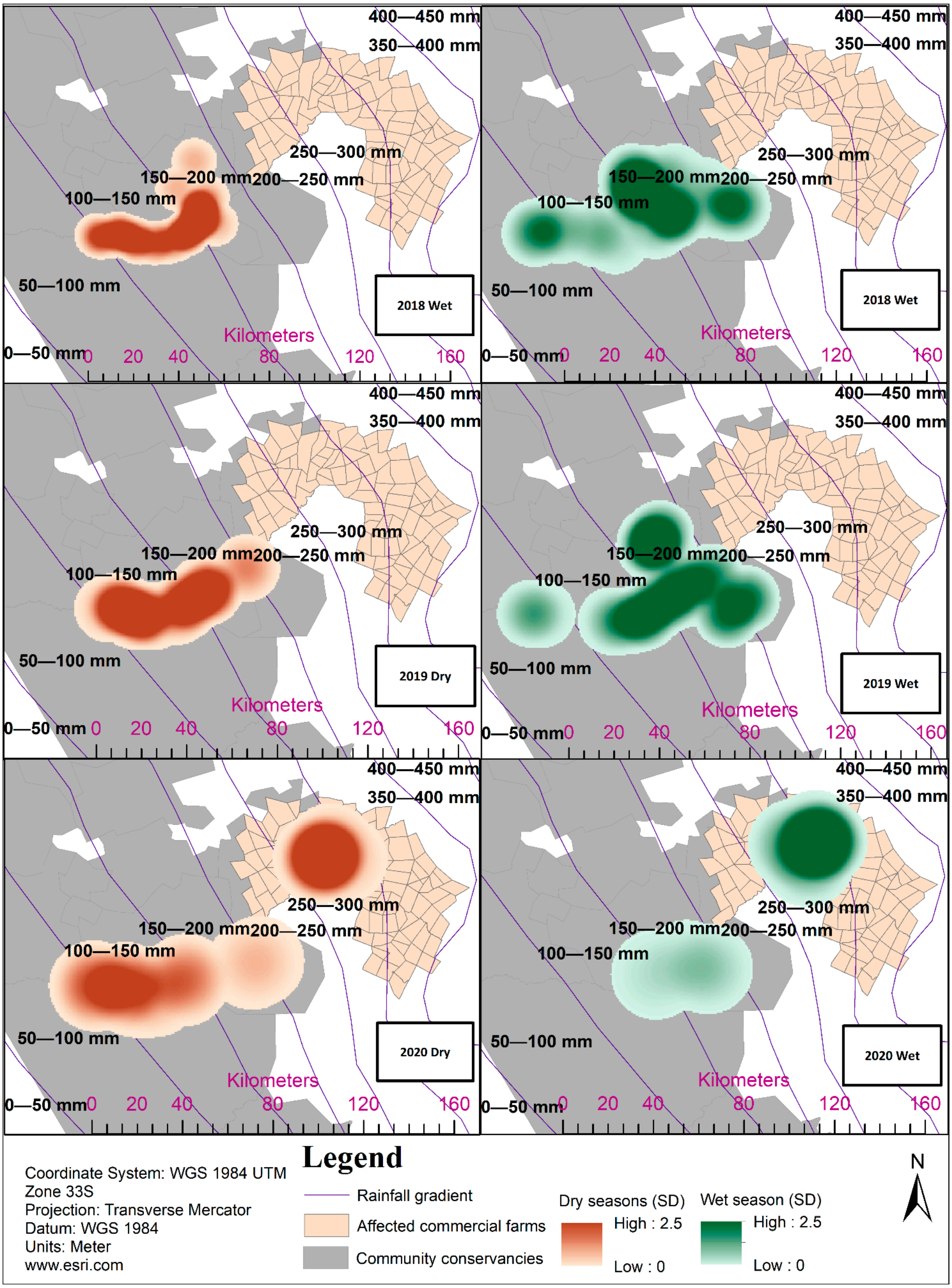

Figure 4. The seasonal distribution of the desert-dwelling elephant population during the dry and wet season in the years 2018, 2019, and 2020.

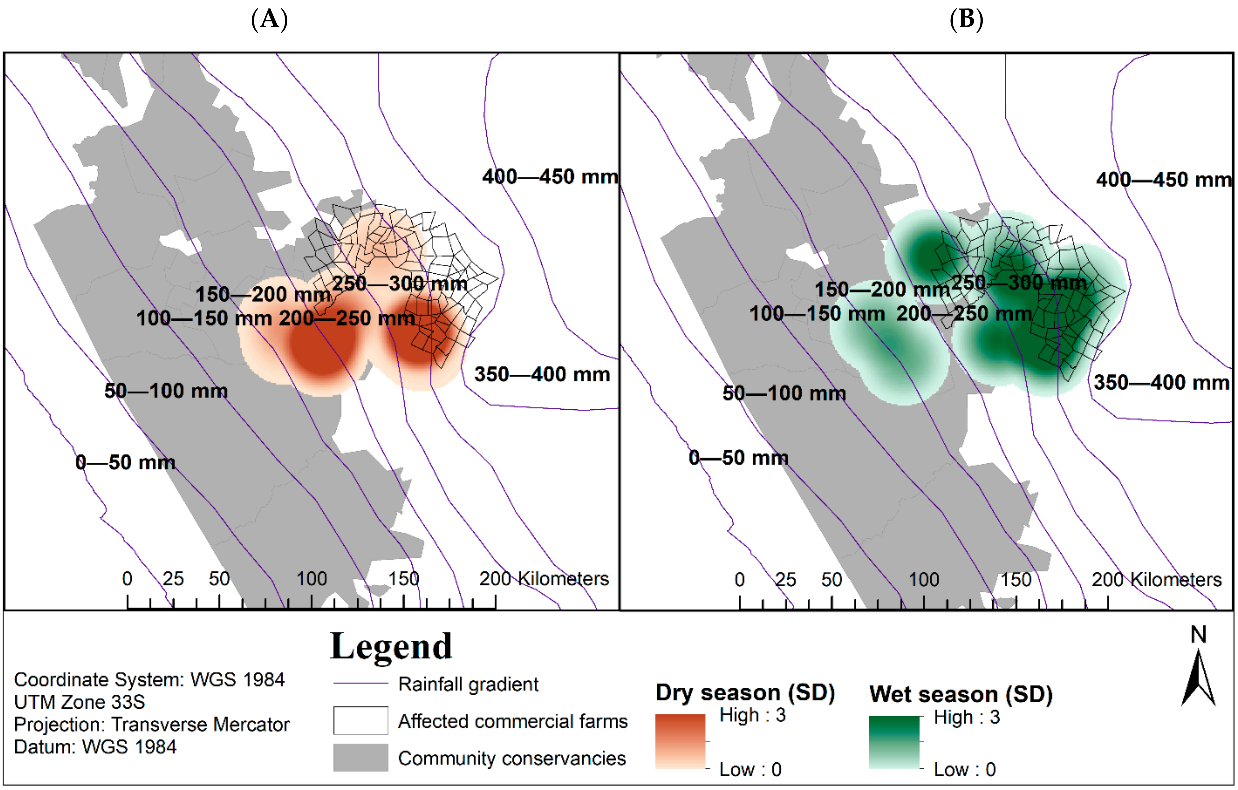

Figure 5. The seasonal distribution of the semi-desert-dwelling elephant population over the wet season (January to June) (**A**) and dry season (July to December) (**B**), combined for the years 2018–2020.

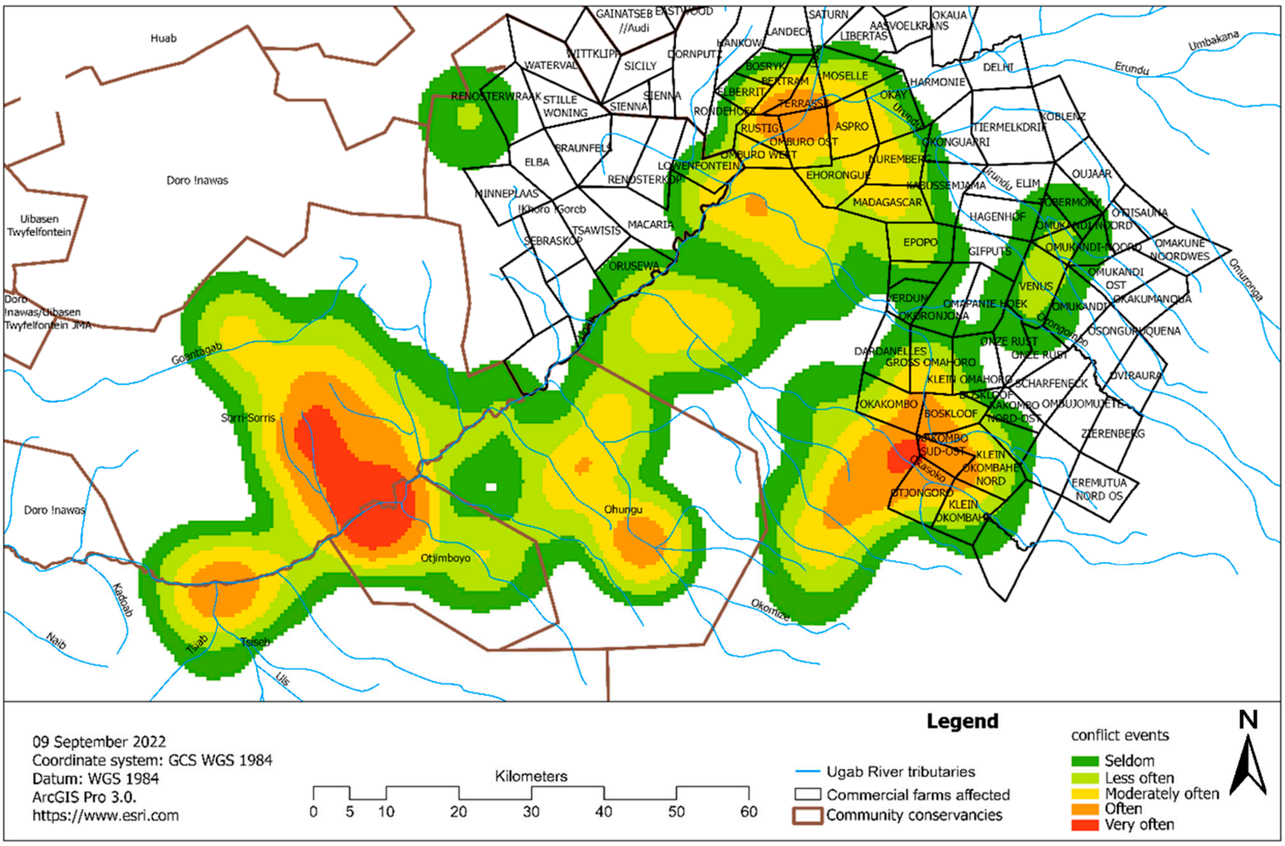

Figure 6. Distribution density of the human–elephant conflict events.

Only four waterpoints were often visited in the URLC, as some of them were damaged by elephants or stopped working and were not repaired. Five of the twelve boreholes within a 5.0 km of the main riverbed of this section, as well as two others further away, ran out of water due to the depletion of the groundwater table, eventually drying up.

3.3. Habitat Loss, Gain, Connectivity, and Migration Corridors

A "suitable historic habitat" was considered as a historic habitat that is still occupied by elephants and a ''suitable new habitat" as areas that have been recently occupied by the desert-dwelling elephants (Figure 7) but that were previously occupied by the transitional herds. These areas have a high density of vegetation and suitable vegetation cover for elephants (mostly *F. albida*, *V. erioloba*, and *Colophospermum mopane*).

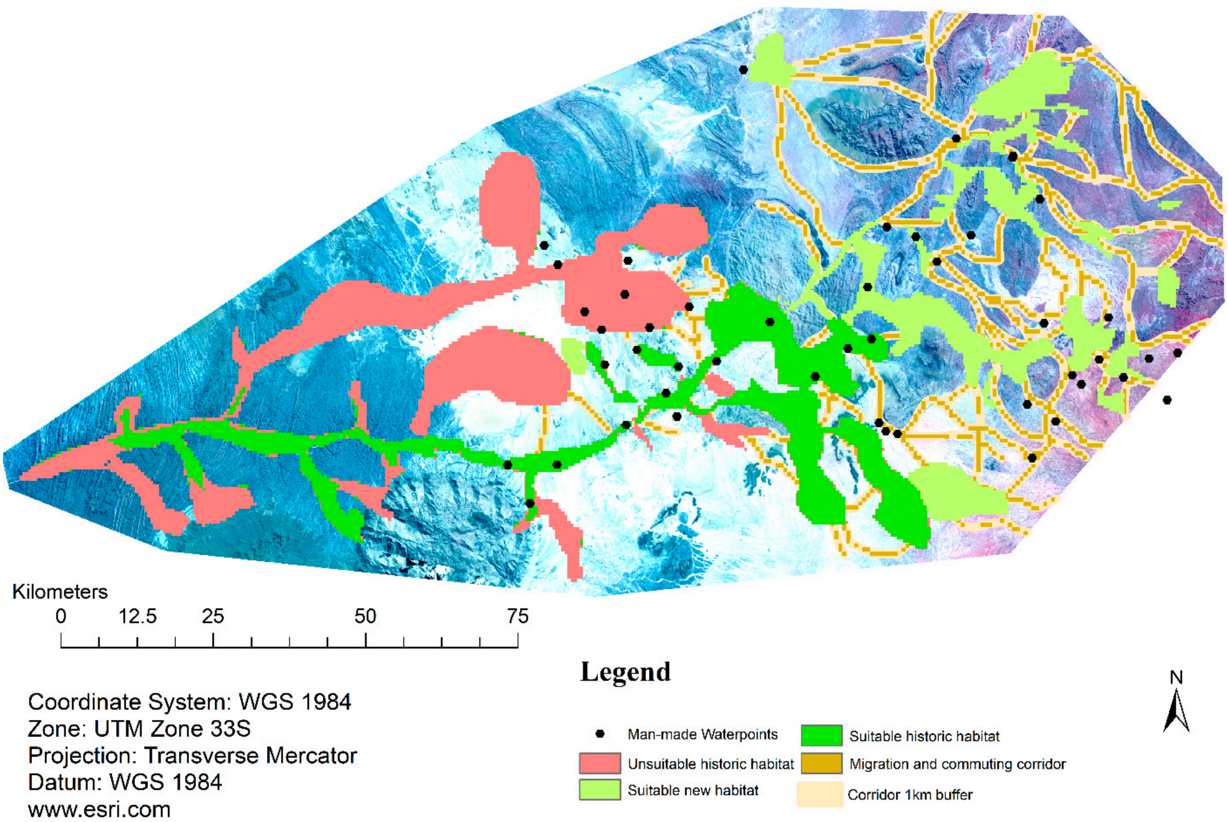

Figure 7. Unsuitable and suitable historic habitats and migration corridors for elephants.

The Ugab River lower catchment herds had 2243 km^2 of suitable historic habitat (Figure 7), which was reduced by 73.0% by 2018. However, the current Ugab River desert-dwelling elephants' overall home range has been estimated at 12,237.0 km^2, demonstrating considerable expansion. It covers more than a third of the Ugab River's catchment (about 29,175 km^2) and is larger than any historical home range for all Namib desert-dwelling elephants reported in previous studies [28,31].

The estimated historical suitable habitat started 30.0 km from the ocean to 150.0 km inland, measured in a straight line, and expanded 53.0 km east of the URUC (Figure 7). Recent expansion has increased the viable habitat by 130.7%, which covers 11.5% of the current elephant home range (Table S5).

3.4. Habitat Modification and Food Availability at the Ugab River Lower Catchment

Over the last 20 years, vegetation has decreased especially in the riverbed, where it used to be abundant and healthy (Figure 8 and Table S5), originating habitats with patches barely vegetated or dominated by dead *F. albida* and *V. erioloba*, (Supplementary Figure S3). Between 2000 and 2006, the percentage of SVeg cover increased by 4.0%, but this value reduced in 2007 and dropped sharply between 2010 and 2015 (Figure 8). Images captured in the field (Supplementary Figure S3) and matched with satellite images confirmed that many large *F. albida* trees mostly died from 2012 onwards. The PUVeg cover decreased every year between 2000 and 2020, affecting the availability of PHVeg.

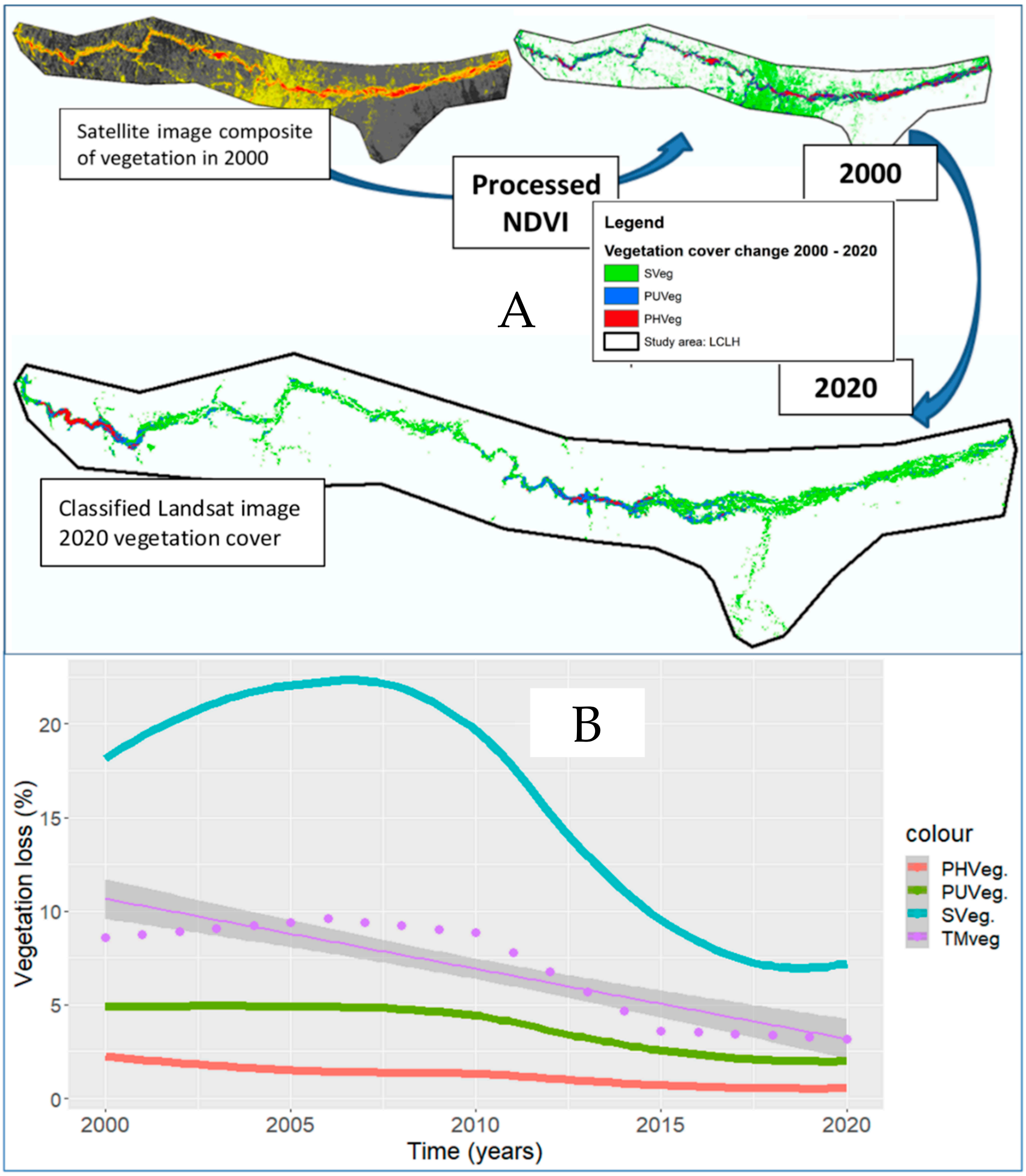

Figure 8. Vegetation changes in the Ugab River Lower Catchment. (**A**) Satellite image processed into NDVI, showing the changes between the vegetation cover in 2000 and 2020. (**B**) Percentage of vegetation cover between 2000 and 2020. The vegetation is divided into three categories: seasonal vegetation (SVeg), perennial unhealthy vegetation (PUVeg), and perennial healthy vegetation (PHVeg). (Analysed using ArcGIS Pro 3.0. https://www.esri.com, accessed on 20 March 2021 (**A**) and R 4.3.0, accessed from: https://www.r-project.org/, accessed on 20 April 2023 (**B**) [46].

Overall, it was observed that in 20 years the percentages of SVeg, PUVeg, and PHVeg decreased by approximately 11.5%, 3.0%, and 1.7%, respectively. Clearly, suitable vegetation covers for elephant habitats and palatable seasonal vegetation have declined, making the URLC habitats unsuitable for elephants, which appears to be driving them to new habitats in the URUC. Figure 8 suggests a relationship between the trends in vegetation loss and declining rainfall. These trends also coincide with those observed regarding the increase in temperature (Figure 1), drought events, and number of CDD (Table S1).

4. Discussion

4.1. Vegetation Loss, Climate Change, and Home Range Shift

Vegetation loss is directly associated with the degradation of habitats, as observed in arid and semi-arid environments, and is notably affecting biodiversity [8,100]. Desert elephants are one of many victims of this problem. Elephants are social animals that group together or form herds associated with the dynamics of their society [82]. The movement of elephant herds in the Namib Desert is influenced by the population structure and the environment [76]. Family groups of desert-dwelling elephants—composed of related adult females and their calves or juveniles—often come together or roam within the same river sections (URLC or URUC) or even subsections (LCLH, LCUH, UCLH, and UCUH) at a specific time. Their movement pattern essentially depends on water and food availability in wet and dry seasons, leading them to walk regularly upstream and downstream [30,69,72].

The desert-dwelling elephant home range averaged 12,237 km^2, showing considerable expansion compared to previously recorded data. This information is supported by emerging hot spots estimated by the OHSA model. The home range of desert-dwelling elephants was estimated to vary from 1763 to 2944 km^2 [28] to be about 2776 km^2 for elephants in South Africa's Kruger National Park and 3309 km^2 for elephants in northern Botswana [1]. The large discrepancy between the area obtained in this study and reported in others, regarding elephants from the desert and from non-desert regions, suggests that some drastic events may be affecting the desert-dwelling elephants. Climatic factors such as rainfall patterns influence the amount of food availability, quality, and abundance and can play a significant role in animal movements [28,101]. Thus, this study argues that recent home range expansions in the Namib desert toward transitional areas were due to the changes in elephant behaviours associated with food and water scarcity and historic habitat loss. These causes arise partly due to climate change, which, without giving any truce, will contribute to an uncertain future for elephants.

The drought events recorded over the last ten years in Namibia [74], with eight years declared as a state of emergency at the national or regional level (mostly in the Kunene region) (Table S1) [33], can be linked to the loss of vegetation in the Namib Desert ephemeral rivers. Figure 7 shows the decline in the vegetation cover, especially from 2012, coinciding with the year from which the number of CDD was increasing (Table S2), and the mean annual precipitation decreased (Figure 1). Therefore, the impact of reduced rainfall, high temperature, and severe drought may further pose a great risk to the desert vegetation.

The findings in this study on poor health vegetation differ from 30 years ago [29] and revealed a large-scale die-off of *A. erioloba* and *F. albida*. This vegetation is preferred by elephants, with *F. albida* playing an important role in the presence of elephants at the springs, as it is downstream that this abundant species offers them shelter. Elephants are developing an interest in consuming reeds and wild *Tamarix* sp., which are less nutritious and contain high amounts of salt [41], and this appears to be happening as a consequence of the loss of the highly nutritious seedpods of Ana trees (*Faidherbia* sp.) and other species.

Previous studies have not investigated how species that inhabit zones of highly underground water-dependent vegetation may be forced to shift their habitats. Desert elephant habitats are losing vegetation, and this event in arid environments can be associated with reduced rainfall and underground water depletion due to over abstraction [64]. Thus, the decrease in groundwater may be linked to the drying up of the natural springs (Supplementary Figure S3). This is leading desert-dwelling elephants to rely on artificial water points such as boreholes to access water (Table S3 and Supplementary Figure S2), ultimately changing seasonal movement behaviour compared to that of a similar population observed in Legget (2006) [30].

Many studies of elephant–vegetation interactions in Africa have focused more on analysing how surface water influences elephant migration [8,100,102,103] or how vegetation is impacted by human–livestock–elephant pressures [58–62,65]. Although this is important, it is argued here that there is an urgent need of analysing the impact of extreme droughts and prolonged groundwater abstraction in arid environments, especially on ephemeral rivers' groundwater flows and riparian vegetation changes. It can only be expected that frequent extreme drought events (Table S1) and poor annual rainfall will further minimise the rate of aquifer recharge. Consequently, this will reduce the water available at natural springs for elephants to dig and for humans to extract.

The recent policy on elephant conservation and management of the Ministry of Environment, Forestry and Tourism (2021) [23] presented that the elephant population growth rate is increasing between 4.2% and 6.5%, which is why the species is expanding into new areas across the country, most notably Omatjete, Kamanjab, Manketi, and Katwitwi. However, local populations such as the desert-dwelling and semi-desert-dwelling elephant populations in the Omatjete area are not growing due to low calf survival rate observed, even though the arrival of desert-dwelling elephants in the area may suggest that named-conservation actions, including the auctioning of 30 live elephants in 2021 as a conflict control measure [104,105], may also affect the population's stability and ability to sustainably provide ecological and economic services.

It should be noted that the expansion of the home range reported here does not mean population growth. Furthermore, the results suggest that the decline in the availability of important resources within historic elephant habitats is causing their home range shift (Figure 4), contributing to the establishment of new habitats (Figure 7). This, in turn, is leading to emerging conflict hot spots, further endangering this ecotype.

4.2. Farmers and Human–Elephant Conflict

For conservation to succeed, an integrated decision-making approach is needed that considers scientific methods with social values [54,106–108]. An integrated decision-making approach validates the fundamental community-based natural resources management (CBNRM) strategy on sustainable resource use in Namibia, including elephants. However, the prevailing HEC still places significant responsibility on the CBNRM program [109]. Emerging conflict hot spots, such as Omatjete (within the Ugab River upper catchment (Figure 6)), Kamanjab, Manketi, and Tsumkwe [23,105], are evolving because of limited food availability and lack of water infrastructure for wildlife.

The water infrastructure built at farms in the past rarely provided drinking dams for elephants, contributing to greater competition between wild animals and farmers in accessing these water points. The community waterpoints in communal areas of Erongo and Kunene regions are often placed in the middle of villages—to be easily accessible to the residents (humans)—yet, elephants coming to drink at the same water points are forced to walk through the villages, leading to a dangerous encounter with people that are commuting between their neighbouring homesteads. Based on these observations, building specific dams out of villages for elephants to drink could be a strategy to reduce dangerous encounters and conflict.

Increasing tourism development facilities has also led to the drilling of new boreholes for water abstraction, whereas communal farms continue to expand, accompanied by agricultural and livestock practices that require large amounts of water [17,35]. Such anthropogenic activities exert pressure on aquifers, whose recharges are increasingly limited in arid environments [64], as they happen in the region of the Ugab River. Thus, the exploitation of resources for human use, the historic habitat loss for elephants, and the complications of arid environments derived from climate change are linked to the increase in HEC observed at the upper catchments of the Ugab River.

4.3. Restoring Elephant's Historic Habitats

"Can we repair some of the damage humans have done to ecosystems and biodiversity?" [110]. Ecosystem restoration is an exciting concept, but it should be considered a secondary option behind the conservation of nature [111]. For example, desert-dwelling elephants survived the harsh conditions of the desert for many years, but the developments of unsustainable farming practices have had a severe negative impact on the megafauna habitats, suggesting that conservation strategies have not been effectively implemented.

The need to restore the URLC section is more complex than an initial restoration process. Regarding vegetation, it is important to mention that few young *F. albida* and *A. erioloba* have been recorded in ephemeral rivers [58,59], and, throughout this work, it was also shown that these species are disappearing from the Ugab River mainly due to large tree die off (Supplementary Figure S3). Therefore, planting indigenous tree species unique to this river system is critical to restoring lost vegetation. In turn, plants require more water for seeds to germinate, and limited rainfall affects the chances of new seed germination [112].

The same can be said for elephants that can no longer dig for water because the water table at the springs has fallen to 1.5 m, which is below the deepest accessible level of 1 m previously recorded in 2013 [70], after two successive drought events (Table S1). Although it is believed that habitat restoration can only occur with minimal human interference (rehabilitation), several aspects are required to achieve an entirely functional ecosystem, such as planting of trees [40], protection of seedlings, and reducing water abstraction [113]. Thus, the restoration of Namibia's ephemeral river habitat requires a combination of the two perspectives, with human intervention required for reforestation as a near-term solution [40].

5. Conclusions

The combined effects of reduced rainfall, frequent droughts, human demand for groundwater abstraction, and pressure on habitat patches in the Namib Desert have negatively impacted water availability, leading to vegetation loss and large tree die-off. As a result, elephants are expanding their home range and establishing new habitats upstream, out of the desert. The new habitats are established within commercial farms, whereas some farms are in commuting and migration corridors. Such emerging commuting patterns contribute to the HEC, and these conflicts may not only be responsible for the killing of elephants by farmers but also for endangering livestock and human life.

Reducing the number of livestock in the desert could help reduce pressure on vegetation and reduce the amount of water abstracted. The latter is particularly important, as the abstraction of water in large quantities has contributed to the reduction in underground water flow, leading to the drying up of natural springs. However, as the chances of recruiting young trees are low due to limited rainfall and severe droughts, this solution alone is not enough. Thus, assisted planting and protection of important tree species (*F. albida* and *V. erioloba*) would help to restore the riparian vegetation that supports elephants and other rare and endangered species, such as the black rhinos.

Another option is to provide financial support to local organisations in the area to sensitise the farmers to coexist with elephants and teach them about elephant behaviours to reduce retaliation killings. The killing of elephants for self-defence or fear is a reality and may increase as new conflicts emerge in areas where people are less familiar with elephants. Locating elephant drinking dams from the centre to the outskirts of the villages can considerably reduce conflict and open doors to coexistence between farmers and wildlife. Lastly, Namibia has a high tourism potential for locals to generate income. Shifting into wildlife farming would reduce pressure on vegetation, and game species in Namibia are better adapted to the dry conditions than livestock, thus paving the way for sustainable income generation through eco-tourism. For this, it would be crucial to obtain policy support and capital investment for tourism infrastructure from the central government and the private institutions. That does not only create job opportunities in the conflict's hot spot but also reduces reliance on livestock that consume more water in turn, which is negatively affecting the entire ecosystem downstream.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151612400/s1, Supplementary Figure S1: Estimated elephant distribution in Namibia; Supplementary Figure S2: Waterpoints frequency visits; Supplementary Figure S3: Dead vegetation; Table S1: Major climate events; Table S2: Climate observation data; Table S3: Water infrastructure and conflict events; Table S4: Elephant home range; Table S5: Vegetation cover. However, raw data with physical descriptions of the area or coordinates will not be publicly available to uphold and promote the security of free-roaming species in the region but may be requested from the corresponding author on reasonable grounds.

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