

Zimbabwe Ecological Conservation Assessing Effects of Urban Development and Drought on Tree Health to Protect White-Backed Vulture Nesting Sites in Zimbabwe

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Abstract: Despite its crucial role in the sub-Saharan African ecosystem, the white-backed vulture (*Gyps africanus*) faces extinction due to the increased mortality rates of nesting trees caused by drought and elephant damage. During droughts, African elephants (*Loxodonta africana*) cause increased damage around waterholes, leading our partners – Connected Conservation Trust and Victoria Falls Wildlife Trust – to investigate the connection between waterholes and the damage to white-backed vulture nesting trees. We used imagery from Landsat 5, Landsat 8, and Landsat 9 to assess vegetation health and landscape change from 1994 to 2024, through Normalized Difference Vegetation Index (NDVI) assessments and land use and landcover (LULC) classification, to examine the impacts of elephant aggression and climatic conditions. We examined these changes in the context of waterhole locations, nesting sites, and environmental factors to provide insight into their relationships. Within an 8-kilometer radius around waterholes, vegetation health declined since 2020, suggesting extensive elephant damage following a major drought. In 2024, we found that 95% of vulture nesting sites were within 8 kilometers of a water source, suggesting that the nesting sites will be increasingly impacted by elephants and other wildlife traffic. Overall, vegetation health did not decline significantly; however, vegetation types are becoming sparser, with 43% of woodlands converted to less tree-dense types. As vultures prefer nesting in tall trees on the border of open land, these land use changes could limit potential nesting sites. While NDVI and LULC from Landsat imagery were feasible methods for this study, the image resolution limited the detail possible to detect. Nevertheless, our findings demonstrate the need for further conservation efforts.

Key Terms: Landsat, land use and landcover, normalized difference vegetation index, Zimbabwe, change analysis

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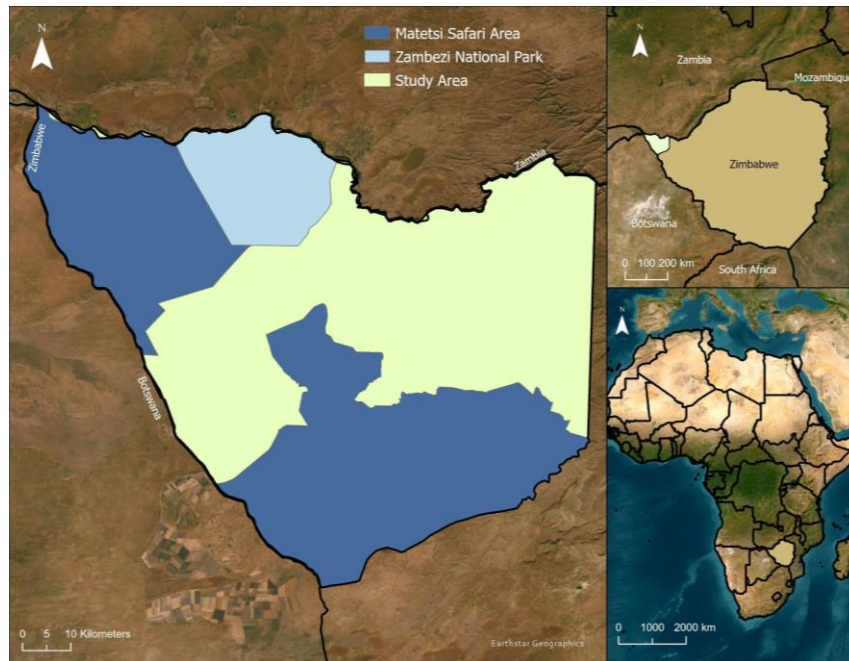
1. Introduction

The white-backed vulture (*Gyps africanus*) is vital to the sub-Saharan African ecosystem. Its diet alone is responsible for neutralizing pathogens, preventing the spread of dangerous bacteria and viruses, and suppressing harmful insect populations (Zvidzai et al., 2024). Additionally, they provide crucial ecosystem services by recycling carcasses and facilitating nutrient cycling (Phipps et al., 2013). However, over the last three decades, this keystone species experienced a rapid population decline due to the unprecedented mortality rates of their nesting trees and is now critically endangered (IUCN, n.d.). Anthropogenic factors, such as urban expansion and climate-induced drought, have introduced additional environmental challenges for wildlife. Specifically, African elephants (*Loxodonta africana*) have increasingly expressed their aggression towards trees that are essential nesting sites for vultures. Elephants are landscape engineers through their habitual behaviors, resulting in tree branch removal, bark stripping, or tree toppling, all of which leave vegetation vulnerable to fire and insect infestations (Cook et al., 2025). These behaviors are often more aggressive during droughts, and their impacts are concentrated around waterholes where elephants congregate due to the availability of resources (Szott et al., 2019).

Due to the pervasive nature of these conservation concerns, extensive research exists attempting to understand and address them. Previous studies utilized remote sensing to inform similar projects, including Earth observations from Landsat 4 and 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI), which guided our study. Normalized Difference Vegetation Index (NDVI) analyses of Landsat data of Zimbabwe were used to analyze forest cover and density change in the Upper Manyame sub-catchment, vegetation decline and recovery in the Muzvezve sub-catchment, and agricultural expansion in the Kavango-Zambezi Region (Bradley et al., 2021; Dzawanda & Ncube, 2020; Zvobgo & Tsoka, 2021). Another study utilized the NDVI Coefficient of Variation to measure variability in vegetation cover and assess changes in vegetation heterogeneity due to elephant densities near artificial waterholes in Hwange National Park (Dzinotizei et al., 2018). Utilizing land use and landcover (LULC) analysis is advantageous for visualizing ecological conservation and anthropogenic impacts on the landscape. Numerous studies used LULC analyses to examine deforestation hotspots in the Muzvezve sub-catchment as a result of urban growth and to identify drivers of change in the Hurungwe District (Dzawanda & Ncube, 2020; Sibanda & Tsuyuki, 2022). While remote sensing provides notable data, GPS technologies are also valuable resources for conservation studies. After capture and tagging, GPS tracking technology estimated spatial home range overlap zones, movement patterns, and protected area usage for the white-backed vultures to inform conservation planning (Phipps et al., 2013; Zvidzai et al., 2022). Telemetry data from GPS-collared elephants examined their space use and foraging behavior movement in Hwange National Park (Mlambo et al., 2021).

This study partnered with the Victoria Falls Wildlife Trust and the Connected Conservation Trust. The Victoria Falls Wildlife Trust works to sustain ecosystems and promote conservation within southern Africa through wildlife rescue and rehabilitation. Connected Conservation Trust addresses human-wildlife conflict through ecological-based community solutions, such as elephant GPS tracking and technical training. One of their unique solutions uses chili as a wildlife deterrent to mitigate elephant aggression and tree destruction (Karidozo & Osborn, 2015; Langbauer et al., 2021). These organizations currently work together to address concerns in the Matetsi Safari Area and Zambezi National Park (Figure 1). While many conservation areas within Zimbabwe have been more extensively researched (Valeix, 2011; Zvidzai et al., 2022), the Matetsi Safari Area and Zambezi National Park regions are under-studied by comparison. Their past work examined the elephant's impact on communal farmers, as elephants have grown more aggressive in response to wildlife tourism (Osborn & Parker, 2003; Szott et al., 2019). These organizations partnered with NASA DEVELOP to assess elephant movement in conservation areas. The growing human and elephant populations within the region further compound these issues (Dzinotizei et al., 2018; Matsa et al., 2021). One of their current objectives focuses on white-backed vulture nest data, as well as tracking and counting nests in the region to study the relationship between elephant aggression towards nesting trees and artificial waterholes. In areas where safaris and ecotourism are becoming increasingly popular, artificial waterholes are drawing growing

wildlife traffic to the area. By examining changes in vegetation health and landcover from 1994 to 2024, we will evaluate the impact of artificial waterholes and its implications for white-backed vulture nesting sites.



ArcGIS basemap credits: Esri, Earthstar Geographics, Kavango Zambezi Transfrontier Conservation Area
Figure 1. Protected lands within the study area (left), the study area within Zimbabwe (top right), Zimbabwe located within Africa (bottom right)

Our main project objectives aim to utilize NASA and European Space Agency’s (ESA) Earth observation data to compare NDVI analyses from 1994 to 2024 for major vegetation changes and map artificial waterholes with white-backed vulture nesting sites to understand the relationships between these factors. This study supports the partners’ missions by informing them of key factors contributing to decadal changes in LULC, vegetation health, and insecurity in white-backed vulture nesting sites. It also provides our partners with tools to identify which areas need greater conservation efforts to advocate for reducing tourism and managing human-wildlife interactions. Additionally, we designed a brochure that our partner organizations can use to effectively disseminate technical information to non-technical audiences.

2. Methodology

2.1 Data Acquisition

Our team used NASA’s Landsat 4 and 5 TM, Landsat 7 ETM+, and Landsat 8 and 9 OLI satellite sensors, to derive vegetation health indices and LULC changes. We primarily worked with Landsat Collection 2 Level-2 data with a 30m spatial resolution for both our vegetation health and landcover classification analyses (Table 1). We selected multiple, cloud free (<5%) images to cover the entire study area. We conducted decadal NDVI analyses from 1994 to 2024, and annual NDVI analyses from 2014 to 2024 using imagery taken in August – October, at the end of Zimbabwe’s dry season. For the earlier years (1994, 2000, and 2004), we used Landsat 4 & 5 TM data, and for more recent years (2014 – 2024), we used Landsat 8 & 9 OLI data. For LULC analysis, we acquired imagery near the end of Zimbabwe’s wet season in March – April for 1995 and 2024. This data was loaded into ArcGIS Pro 3.4 for processing.

Table 1
Earth Observations

Dataset	Spectral Bands/Features	Spatial Resolution	Time Period	Usage	Source
Landsat 4-5 TM	Band 3 (Red): 0.63 - 0.69 μm , Band 4 (NIR): 0.76 - 0.90 μm	30m	Aug. 1994, 2000, 2004	NDVI analysis of vegetation health	USGS Earth Explorer
Landsat 4-5 TM	Band 1 (Blue): 0.45 - 0.52 μm Band 2 (Green): 0.52 - 0.60 μm Band 3 (Red): 0.63 - 0.69 μm Band 4 (NIR): 0.76 - 0.90 μm	30m	Mar. 1995	Landcover classification and analysis	USGS Earth Explorer
Landsat 8-9 OLI	Band 4 (Red): 0.64 - 0.67 μm , Band 5 (NIR): 0.85 - 0.88 μm	30m	Aug. - Sept. 2014 - 2019	NDVI analysis of vegetation health	NASA Earthdata Search
Landsat 8-9 OLI	Band 4 (Red): 0.64 - 0.67 μm , Band 5 (NIR): 0.85 - 0.88 μm	30m	Aug. - Sept. 2020 - 2024	NDVI analysis of vegetation health	USGS Earth Explorer
Landsat 8-9 OLI	Band 2 (Blue): 0.45 - 0.51 μm Band 3 (Green): 0.53 - 0.59 μm Band 4 (Red): 0.64 - 0.67 μm Band 5 (NIR): 0.85 - 0.88 μm Band 6 (SWIR1): 1.57 - 1.65 μm	30m	Mar. 2024	Landcover classification and analysis	USGS Earth Explorer

2.2 Data Processing

2.2.1 NDVI Calculations

To begin our NDVI analysis for each year of interest, we created mosaic datasets for the Red band and the NIR band, and then added the adjacent, corresponding raster images into each mosaic dataset to align them into one image. We exported and composited the rasters into a single raster dataset, then extracted the composite using our study area mask to only visualize our relevant region. After these steps, we used the Raster Calculator tool in ArcGIS Pro to calculate NDVI values (Equation 1). These raw NDVI outputs underwent further processing (Figure 2). The raw raster outputs had values ranging from -1 to 1, with -1 representing water and bare land, and 1 representing the healthiest vegetation. We edited the symbology and used a Minimum Maximum stretch type with unique values set to 0 to 0.4 to visualize the most important data.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

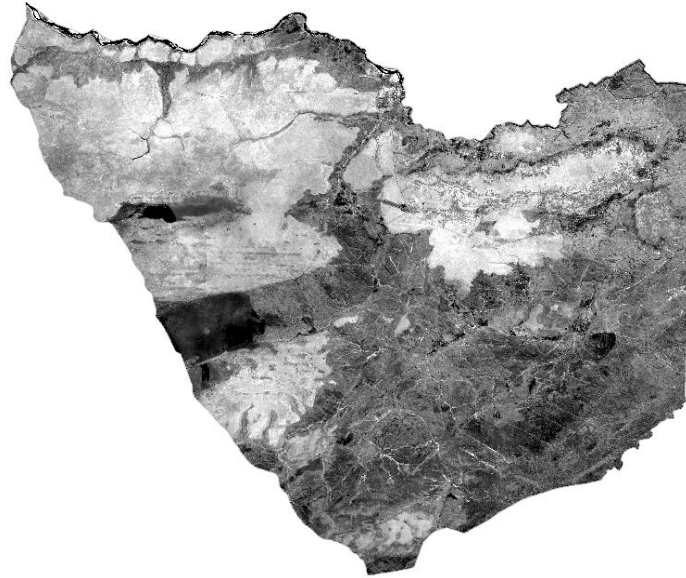


Figure 2. A composited 2024 NDVI image clipped to the study boundaries encompassing Zambezi National Park and Matetsi Safari Areas

2.2.2 LULC Classification

Similar to NDVI, we created mosaic datasets for each relevant band from the April 2024 satellite imagery: Band 2 (Blue), Band 3 (Green), Band 4 (Red), and Band 5 (NIR), and composited them into a single raster dataset to clip to the study area. We switched between displaying false color (Band 3, 4, and 5) and true color (Band 2, 3, and 4) images to help us identify landscape types. We classified seven landcover types: woodland, bushland, shrubland, grassland, cropland, water, and bare areas. Woodland refers to tree-dominant and densely vegetated areas, while bushland features shorter, but similarly dense, vegetation. Shrubland areas are covered in shrubs and smaller plants and tend to thrive in drier areas. Grassland areas contain land covered with grass, and cropland indicates areas designated to grow crops. Bare areas include bare soil, desert, and urban/built-up areas, with no vegetation. Lastly, water areas have open bodies of water, including waterholes. For each landscape class that we identified we created a classification schema in the Training Samples Manager to name the classes and training points that we placed in areas we knew belonged to that class. These training points, which we digitized from the basemap imagery in ArcGIS Pro, collected pixel-based surface reflectance data that our classification model applied to the entire study area.

2.2.3 Ancillary data

To conduct further analysis for vegetation health and landcover classification, we obtained annual white-backed vulture nesting sites from 2014 to 2024 and waterhole comma separated value (CSV) coordinates from the Victoria Falls Wildlife Trust (Table 2). We used the XY Table to Point tool in ArcGIS Pro to transform these coordinates into vector point shapefiles and removed all data points outside the study area. These data were used to assess how vegetation health and landcover has changed around those points.

Table 2
Ancillary datasets

Name	Product Type	Data Type	Data Provider	Usage
Annual white-backed vulture nesting sites from 2014 - 2024	CSV file with coordinates, converted to point shapefile	Vector	Victoria Falls Wildlife Trust	Analysis including vegetation health and landcover classification
Waterholes	CSV file with coordinates, converted to point shapefile	Vector	Victoria Falls Wildlife Trust	Analysis including vegetation health and landcover classification

2.3 Data Analysis

2.3.1 NDVI Analysis

We compared 2014 – 2024 annual NDVI outputs to visualize how vegetation health has declined and increased over this decade, as this time period was most relevant for our partners to assess recent changes. This decade also had vulture nest data available to conduct proximity analysis. We analyzed change detection from the NDVI outputs over the entire time period and between each decade by entering the individual NDVI outputs from the start and end of each time segment into the Change Detection Wizard in ArcGIS Pro. We used a consistent legend to compare change across the time periods and specified unique ranges of values with the Change Detection Wizard to create rasters containing each relevant range of values as categories. These value range changes included -1 to -0.01 as a decrease in health, -0.009 to 0.009 as no change, and 0.01 to 1 as an increase in health. This visualized the areas with the most intense decline. We used the Summarize Categorical Raster tool in ArcGIS Pro to convert each decade’s individual categorical raster into a summary table, calculated the area in square kilometers within each change category, and visualized the results as bar charts and percentages for comparison.

2.3.2 LULC Analysis

We used the Summarize Categorical Raster tool to calculate the number of pixels for each landcover class in 1995 and 2024. We multiplied the pixel count by the area of each pixel and converted it to square kilometers to conduct change detection for this analysis. Focusing on the most relevant classes, such as woodland, bushland, and bare area, to determine how landcover has varied and morphed into other classes. We visualized these changes by comparing both the relative area of each class, as well as the percentage of change from 1995 to 2024.

2.3.3 Other Analyses

We examined the relationship between vulture nesting sites, waterhole presence, and environmental factors, including NDVI and LULC. Using the Extract Values to Table tool in ArcGIS Pro we extracted the NDVI value to nests in the corresponding year, then averaging the overall NDVI value for each year, we plotted the average NDVI of nesting trees annually as a line chart to visualize how vegetation health has changed with vulture nesting sites over time. We used the Extract by Mask tool in ArcGIS Pro to identify the landcover class for each vulture nest and quantified the number of nests within each class into a bar graph to determine what land type(s) vultures prefer to nest in. To evaluate the relationship between vulture nests and waterhole data, we created 3 km, 5 km, and 8 km buffers around the waterhole data to conduct a proximity analysis of the distance between the waterhole points and the vulture nesting sites. We conducted a spatial join between the nests and waterhole buffers to summarize the number of nests within each buffer area. Also, we overlaid the NDVI outputs with the buffered waterholes to visualize the average vegetation health in the surrounding waterhole areas and determined how vegetation health changed as distance from the waterholes increased.

3. Results

3.1 Analysis of Results

3.1.1 NDVI Results

The annual dry season NDVI outputs examining the 2014 – 2024 decade showed how the landscape and vegetation health changed over this period. One major effect on vegetation health was burn scars from fires. This resulted in a decline in vegetation health over the period, with burn scars peaking around 2023. From these NDVI results, we observed a general decline in vegetation health (Figure A1). We also observed more healthy vegetation from 2015 to 2019. From 2020 to 2024, the NDVI values decreased again, and we observed more degraded vegetation and burn scars cropping up. Over the entire study period, there were vegetation health increases in some areas, while the most recent decade showed an overall decline in vegetation health. Additionally, a comparison between the 1994 and 2024 NDVI outputs showed that, while there was vegetation rebound in some areas, there was also a decline in vegetation health over the entire study period (Figure A1).

3.1.2 NDVI Change Detection Results

The NDVI change detection analysis showed the areas with the most decline in vegetation health, as well as areas with the most increase in vegetation health. From 1994 to 2024, the most significant decline occurred near the southern and western Botswana borders (Figure 3). This change detection analysis output also showed a number of areas with improving vegetation health, particularly near the study area center (Figure 3). Compared to the NDVI results above, the change detection for the entire study period showed increasing vegetation health.

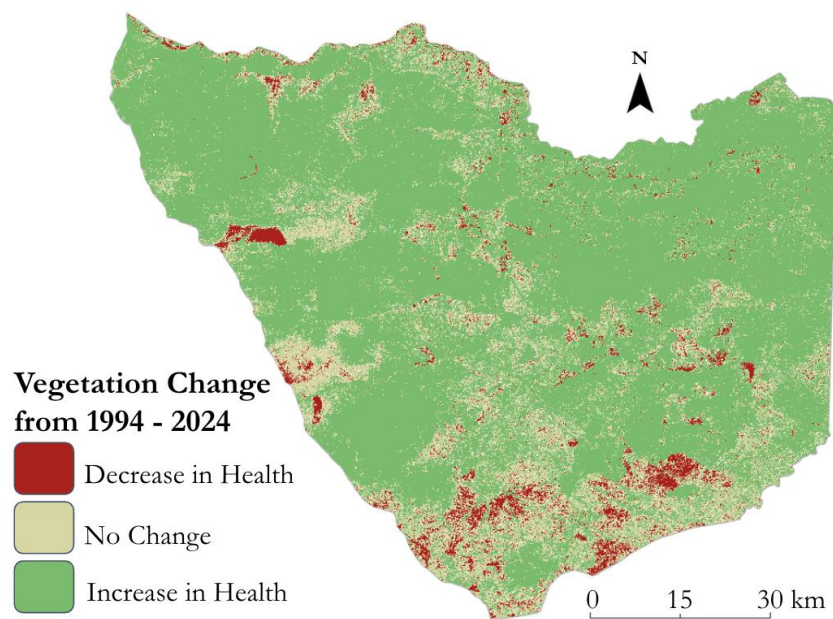


Figure 3. A map showing NDVI Change Detection analysis from 1994 to 2024

We also conducted NDVI change detection analyses for each decade throughout our study period. These change detection outputs showed major decline in vegetation health for each subsequent decade (Figure 4). Generally, we found that the 1994 – 2004 decade shows little vegetation health decline compared to the 2014 – 2024 decade (Figure 4). The 2014 – 2024 decade contained the most decrease to the vegetation health with many red areas throughout the map (Figure 4). These decadal change analyses also indicate a greater decline in vegetation health compared to our entire study period.

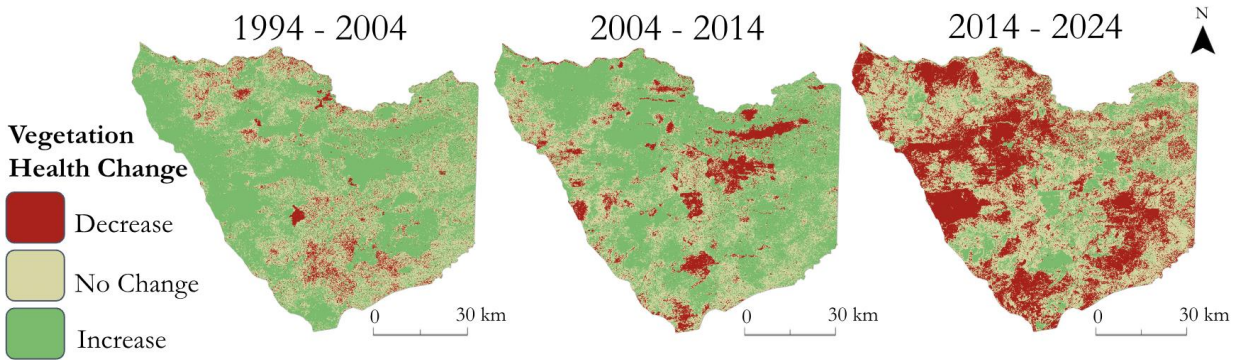


Figure 4. A set of maps showing NDVI Change Detection analysis for each decade within the study period

To compare areas of vegetation health increase and decrease, we plotted the areas of change in NDVI value for each decade. The NDVI value change resulted in 3 prominent classes: Decrease in Health, No Change, and Increase in Health. Compared to the prior decades, 2014 – 2024 shows a major area expansion for negative NDVI change and vegetation health decline (Figure 5). The 2014 – 2024 decade had 24,730 km² of land that experienced vegetation health decline. The previous decades, 1994 – 2004 and 2004 – 2014, had less land that experienced vegetation health decline, with 5,019 and 7,382 km², respectively (Figure 5). 2014 – 2024 also had considerably less land that experienced an increase in vegetation health compared to the previous decades. From 2014 – 2024, 9695 km² of land experienced increasing vegetation health. The previous decades, 1994 – 2004 and 2004 – 2014, had more land that experienced increasing vegetation health, with 38,619 and 37,689 km², respectively.

We also calculated the percentages of land belonging to the NDVI value changes to compare areas of vegetation health increase and decline. Only 15.33% of the 2014 – 2024 decade’s area experienced an increase to vegetation health, while 39.12% of land experienced a decline in vegetation health (Table A1). Throughout the previous decades, we calculated higher percentages of increasing vegetation health and lower percentages of vegetation health decline. From 1994 – 2004, only 7.82% of land experienced a decrease in vegetation health, while 60.16% of land experienced increasing vegetation health (Table A1). From 2004 – 2014, 11.58% of land experienced a decrease in vegetation health with 59.06% of land classed as increasing vegetation health (Table A1). These percentages reinforced the maps above that there was the most increase in vegetation health throughout our entire study period (1994 – 2024). This period contained the smallest area that experienced a decrease in vegetation health with just 4.46% (Table A1). These calculations demonstrated that the entire study period possessed the least vegetation health decline, while the following decades subsequently demonstrated declining vegetation health.

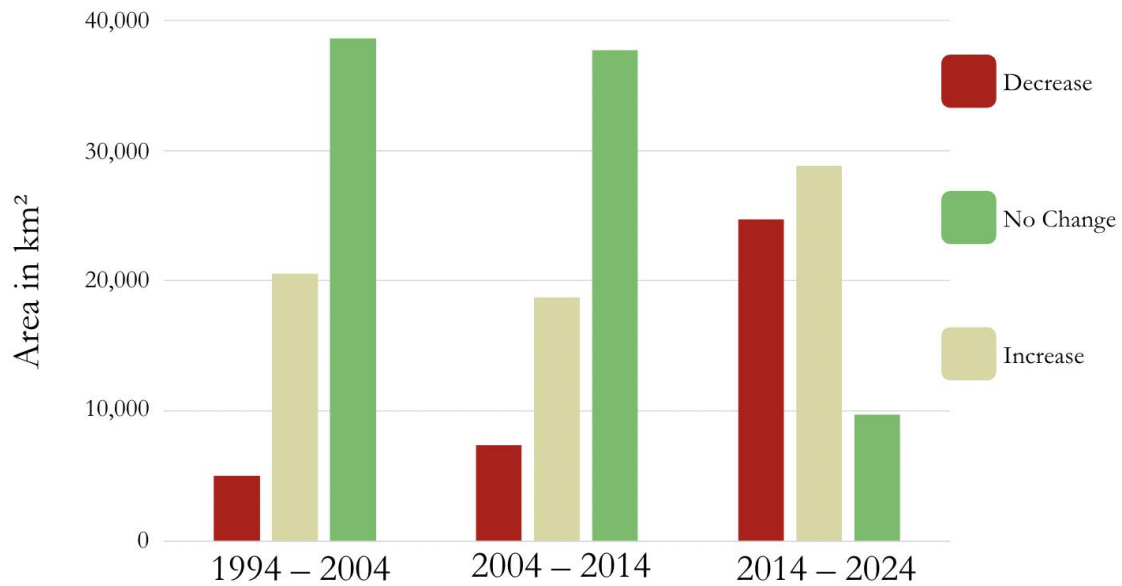


Figure 5. A bar chart showing the area in square kilometers occupied by NDVI change detection values for three decades

The trends seen in overall NDVI change for the decades and study period were also evident in the areas surrounding vulture nesting trees (Figure 6). For 2015 – 2019, the NDVI values suggest that the nesting trees were at peak health but then experienced a steep decline by 2020. From 2020 – 2024, the nesting trees exhibit consistent low NDVI values around 0.14, indicating overall poorer health. While precipitation could play a role, with 2015 – 2016 and 2018 – 2019 being El Niño years and therefore having less rainfall, the vegetation health did not recover when rainfall returned to normal in 2020. Because the NDVI values remain low, it suggests that another factor influences the nesting tree health.

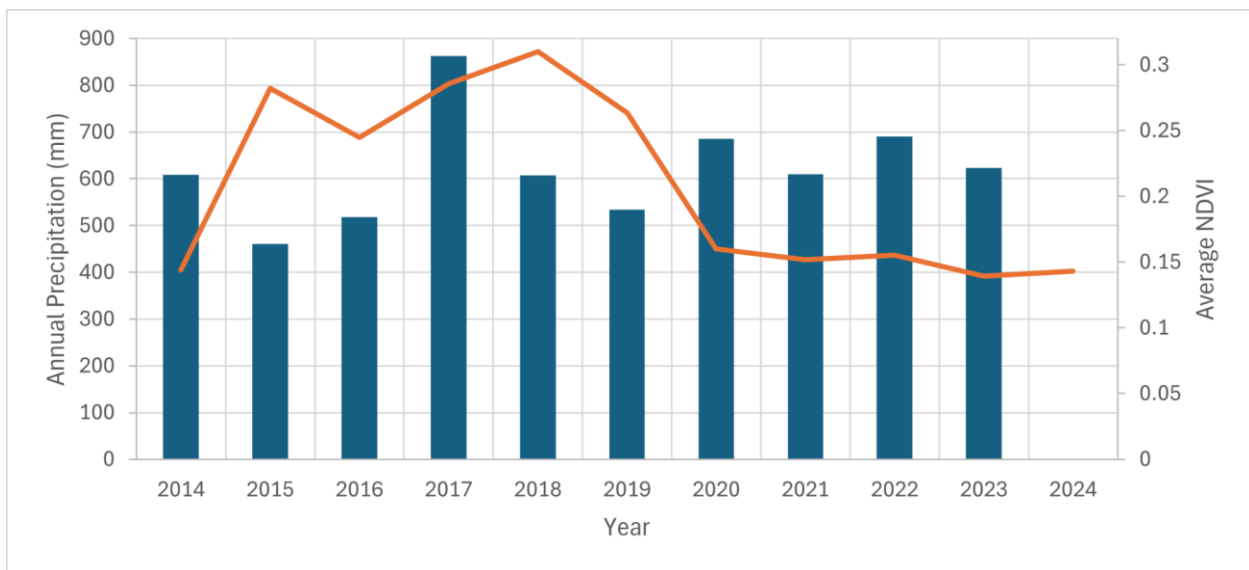


Figure 6. Average NDVI of vulture nesting trees annually from 2014 – 2024 as the orange line and precipitation as the blue bars

Similarly to nests and the overall NDVI, the NDVI around the waterholes decreased sharply in 2020 and remained at low values. However, we did not see any trends of vegetation health changing with increasing proximity to the waterholes (Figure 7). In fact, the NDVI values in the 3 kilometers closest to the waterhole were slightly higher than the NDVI at 5 and 8 kilometers, although all values were very close. The consistency in NDVI values around the waterholes suggests that elephant damage extends to 8 kilometers.

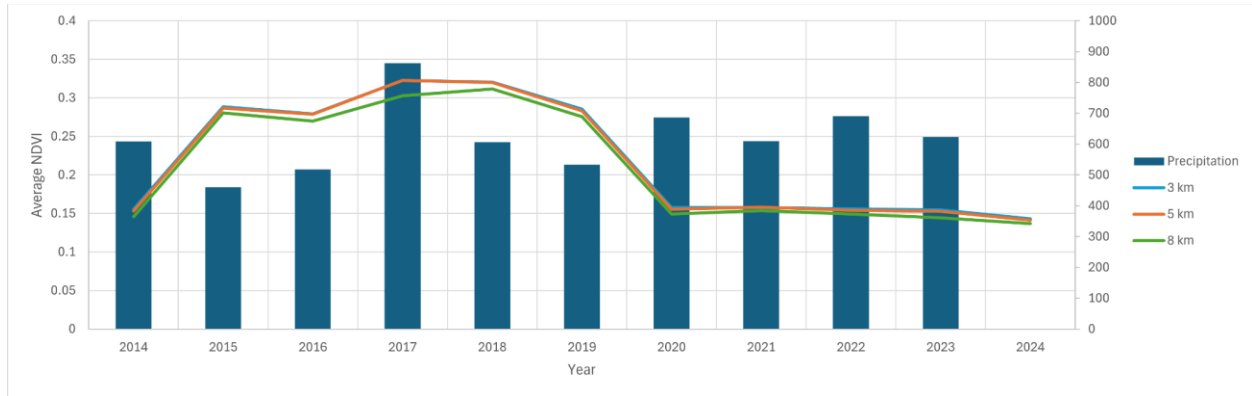


Figure 7. Average NDVI within 3, 5, and 8 km of a waterhole annually

3.1.3 LULC Results

Using the LULC from 1995 and 2024, we showcased the geographic magnitude and pattern of various landcover types including woodland, bushland, shrubland, grassland, cropland, water, and bare areas (Figure 8; Table B1). The LULC map from 1995 highlighted the extensive coverage of woodland and bushland, both of which influence biodiversity and ecological balance. 1995 also showed minimal bare areas, which indicated a well-preserved landscape with limited degradation and soil erosion. The 2024 map displayed notable changes with a large expansion of bare areas and woodland loss.

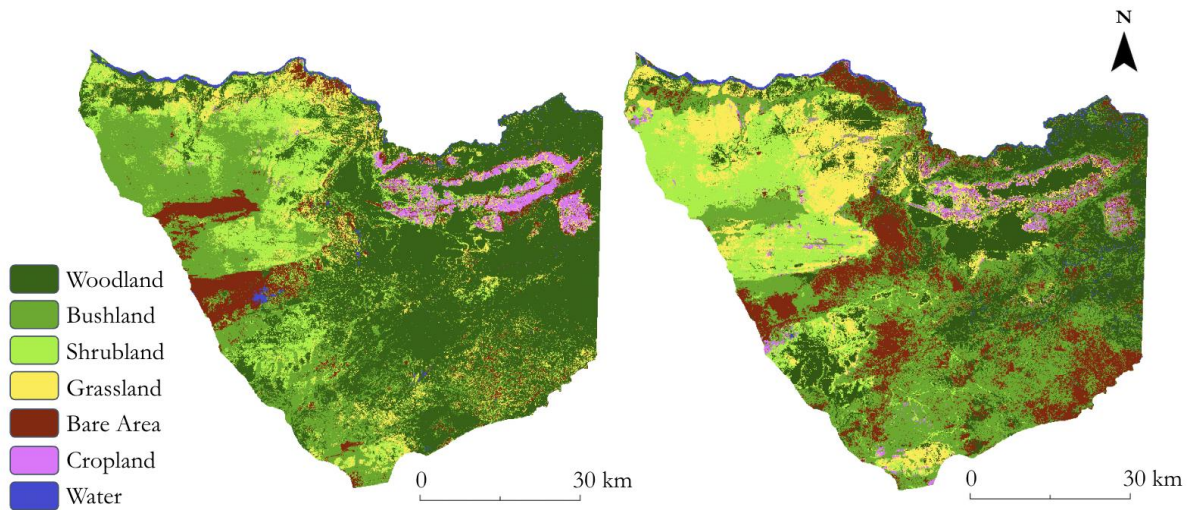


Figure 8. Landcover Classified Maps from 1995 and 2024

We quantified the associated pixel counts and area measurements of each landcover type in square kilometers (Figure 9), then calculated the percent change in these classes from 1995 – 2024. Woodland cover decreased by 42.61%, and cropland by 8.41%. Notable increases during this period included bare areas by 101.73%, shrubland by 16.44%, bushland by 37.17%, grassland by 54.5%, and water by 28.67%.

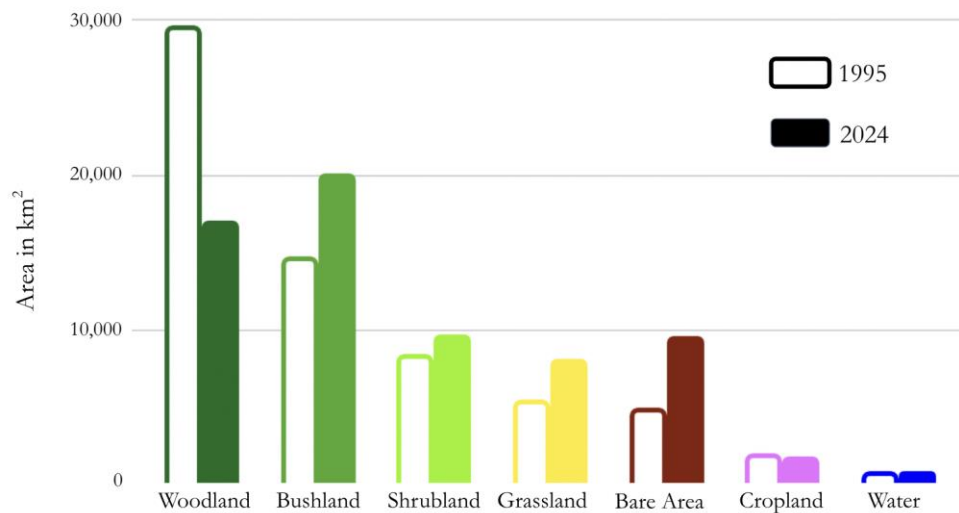


Figure 9. Landcover Area in Square Kilometers from 1995 and 2024

We also examined the landcover types where vultures prefer to nest. The landcover classes from 2024 with the highest nest counts were bushland, woodland, grassland, and shrubland (Figure 10). Bushland area contained the highest count with 76 nests. Woodland had 23 nests, while grassland and shrubland had 15 and 14, respectively. Vultures generally nested in more wooded and tree-dense areas on the border of more open areas (Figure B1). Some of the nests in the bare area were likely in singular tall trees not detected in the satellite imagery.

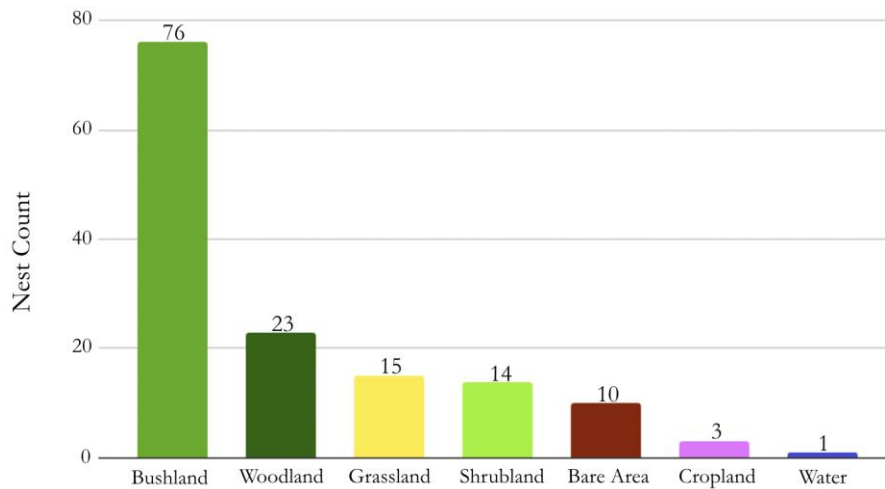


Figure 10. Number of nests per landcover type from 2024

The white-backed vulture preferred to nest in trees with close proximity to water (Table 3). There were higher nest densities in the 3-kilometer buffer surrounding the water holes and the Zambezi River at 255 and 335 nests respectively between 2014 – 2024. As distance from water holes decreased, so did the number of nests. The Zambezi River also had fewer vulture nesting sites further away, but the 5 – 8 km distance contained vegetation hotspots where many vultures nested along the Botswana border, which increased its density. In 2024, 95% of the nesting sites were within the 8 km buffer.

Table 3

Vulture nesting sites within 3, 5, and 8 km distances from a waterhole or the Zambezi River

Distance from Water Source	Nests by Waterholes	Nests by Zambezi River
Less than 3 km	255	335
3 - 5 km	100	122
5 - 8 km	97	296

3.2 Errors & Uncertainties

3.2.1 Burn Scars

We identified several errors and uncertainties throughout the course of our project. One major source of error and uncertainty is burn scars in the region, which vary between years. The burn scars varied in both size and location, with the most burn scars and fires observed in 2023 (Figure A1). These burn scars resulted from both controlled and uncontrolled fires in the area. Fires and burning impact the vegetation health of the area, which increases the difficulty in accurately assessing vulture nesting habits and the overall health of areas they prefer to nest.

3.2.2 Cloud Coverage

Another impactful source of error and uncertainty is cloud coverage. For each year we downloaded satellite imagery data (1994, 2000, 2004, 2014–2024), we set the cloud coverage less than 5%, and in some cases, less than 3%. This limited the days and months available for some years and prevented us from selecting the same day/month for every year for both our vegetation health assessments and landcover classification. Furthermore, cloud coverage from 1994 resulted in selecting imagery from 1995 instead to conduct a more accurate landcover classification. Although we wanted to select imagery from the oldest dates within our study period, data availability limited us.

3.2.3 Uneven Training Points

A final source of error and uncertainty throughout our study is the training points for the landcover classification, which were unevenly distributed across the classes (Table 4). Some classes, such as woodland and bushland, received a high number of training points, while other classes, such as grassland and bare areas, received far fewer training points. The number of training points for each class depended on the pixel variation within a given class. Classes with more training points are more likely to be accurate than classes with fewer training points. We distributed many training points within clusters rather than having them more widely spread, as there was a lot of variability within the clusters, and this was more time efficient. We spoke with individuals from our partner organizations living in the study area, as well, to ensure that we accurately assessed the outputs. Due to time constraints, we did not conduct an accuracy assessment to verify our results so the amount of error and uncertainty, and the reliability of our training points, is unknown.

Table 4

Training points within each class for 2024 classification

Landscape Type	Number of Training Points
Woodland	431
Bushland	124
Cropland	57
Shrubland	52
Water	45
Bare Area	43
Grassland	23

4. Conclusions

4.1 Interpretation of Results

Our results offer insight into the patterns and underlying factors shaping the northwest Zimbabwean landscape, allowing for a deeper understanding of their impacts. The NDVI analyses indicated that burn scars impacted the vegetation health in the region and worsened through time. This complicated the assessments of vegetation health and its interrelation to vulture nesting habits. While large-scale vegetation health decline from 1994 – 2024 was low, the recent years from 2014 – 2024 had reduced precipitation, drier areas, and generally, more burn scars.

Only 10.48% of the study area experienced a striking vegetation health decline, suggesting resilience over the 30-year period. Areas that did not maintain this resiliency may be areas of concern to monitor. The most recent decade demonstrated stark increases in vegetation decline; 66.24% of classified land experienced deteriorating health by 2024, compared to around 20% in previous decades. This suggests that earlier vegetation conditions helped balance the trends overall, but patterns of decline from 2014 – 2024 show a concerning shift in long-term vegetation health. Examining the landscape change from 1995 – 2024 showed the impacts of development and climate-induced drought as well. A 42.61% decline in woodland cover and 8.41% in cropland cover, coupled with the drastic 101.73% increase in bare areas, contributes to biodiversity loss, reduced carbon sequestration, and greater soil erosion. Although shrubland, bushland, grassland, and water areas increased, these shifts from former woodland dominance present mixed implications. While they support enriched biodiversity and flood mitigation, they increase fire risks and land-use conflicts, require careful management, and decrease viable areas for vulture nesting sites. The decline of woodlands may pose a challenge for vultures, as they prefer more wooded and tree-dense nesting areas. While increased bushland cover provides some relief, supporting 76 nests in 2024, white-backed vultures prefer tall trees, around 16-17 meters, which are most abundant in woodland areas. As woodland cover decreased, optimal nesting sites also decreased.

Increased wildlife traffic and elephant aggression around waterholes further complicate these conflicts, as it amplifies the damage to white-backed vulture nesting trees. Vegetation health, particularly around waterholes and vulture nests, has decreased since 2020. In the surrounding 8 kilometers around waterholes, NDVI values did not vary much, suggesting elephant damage around these areas was far-reaching and the vegetation struggled to recover without heavy rains. Since precipitation returned to normal after the 2019 drought, the vegetation health decline in vulture nesting trees could be due to the elephant damage around the waterholes. At least for 2024, 95% of the nests were located within this damaged region, underscoring risks of elephant damage to nesting trees, especially during droughts as they congregate by waterholes.

4.2 Feasibility & Partner Implementation

Ultimately, our implemented methods, including NDVI analysis, landcover classification, and evaluations of waterhole and nest data, were feasible to use as conservation tools. Our results can contribute to our partners' outreach and decision-making objectives, specifically through the analysis of artificial waterhole impacts, white-backed vulture conservation, and woodland recovery. We identified a relationship between waterhole placements and vulture nesting sites, which provides a foundation for the partners to implement informed decisions regarding the future management of these waterholes. These results are important to address these conservation needs and lay the groundwork to tackle broader analysis and future impacts.

5. Acknowledgements

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- **Science Advisor:** Dr. Marguerite Madden
- **DEVELOP Lead:** Dr. Jennifer Mathis
- **Project Partners:** Connected Conservation, Victoria Falls Wildlife Trust
- **Project Coordination Contact:** Brent Bowler

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6. Glossary

ArcGIS – Geographic information system software that provides tools to manage, create, analyze, and share geographic data and maps to support environmental/urban planning and other applications

Bare Area – Areas of land with no vegetation

Biodiversity – Variety of living things in a given area

Buffer – A defined area surrounding a feature of focus

Bushland – Areas filled with dense and bushy vegetation, usually in dry regions

Carbon Sequestration – The process of catching and storing carbon dioxide from the atmosphere to reduce climate change

Change Detection Wizard – A tool in ArcGIS Pro used to identify and analyze differences within datasets to monitor land changes

Composite – Combining multiple datasets into one

Cropland – Areas of land designated to grow crops

El Niño – A climate pattern that causes warming of surface waters in the Pacific Ocean, leading to unusual weather patterns such as heavy rain or droughts

False Color – Map colors that are unrealistic, used to enhance various landcover types for easier identification

GPS – Global Positioning System

Grassland – Large areas of land filled with grass

Landcover Classification – The process of placing areas into categories based on surface type such as forest, ocean, development, etc.

Landsat 4-5 TM – Landsat 4 and 5 Thematic Mapper

Landsat 7 ETM+ – Landsat 7 Enhanced Thematic Mapper Plus

Landsat 8 OLI – Landsat 8 Operational Land Imager

Landsat 9 OLI-2 – Landsat 9 Operational Land Imager-2

LULC – Land use and landcover

Mosaic Dataset – A collection of multiple satellite images assembled together for visualization and analysis

NDVI – Normalized Difference Vegetation Index

NIR – Near Infrared

Percent Change – A calculation to observe the change between two values from different times:

$$\text{Percent Change} = ((\text{New Value} - \text{Old Value}) / |\text{Old Value}|) \times 100\%$$

Raster – A data structure storing information in a grid of cells or pixels

Shrubland – Areas covered in shrubs such as small woody plants

Soil Erosion – The wearing away of the top layer of soil from factors such as water, wind, or human activities which causes the soil's degradation and infertility

Stretch Type – Way to adjust the appearance of map images for simpler interpretation

Telemetry Data – An automated process where data is collected, transmitted, and analyzed from remote systems and/or devices

Training Points – Specific locations plotted in mapping processes to identify landcover types

True Color – Map colors that look the way they would when observed in person

USGS Earth Explorer – United States Geological Survey Earth Explorer

Water – Open bodies of water, including waterholes

Waterhole – A pool, natural or artificial, for animals and plants to more easily access water

Woodland – Areas that are tree dominant which houses diverse animal and plant species

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9. Appendices

Appendix A: NDVI

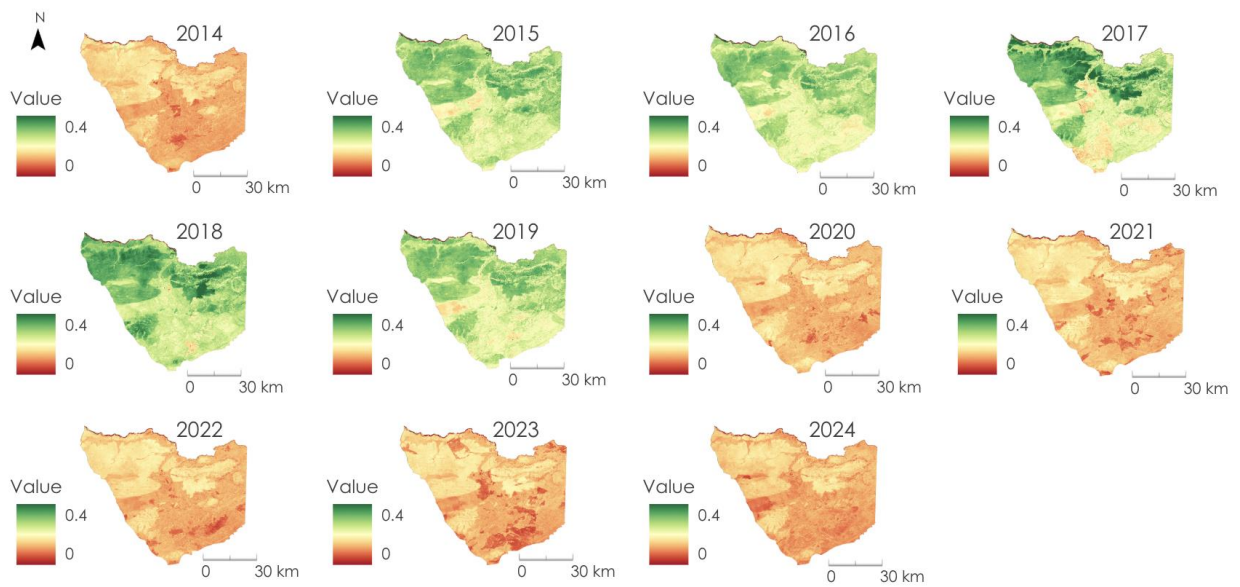


Figure A1. Time Series of NDVI outputs from 2014 – 2024

Table A1

NDVI Change Detection Percents

Vegetation Health Change	Percent in 1994 - 2024	Percent in 1994 - 2004	Percent in 2004 - 2014	Percent in 2014 - 2024
Decrease in Health	4.46%	7.82%	11.58%	39.12%
No Change	18.41%	32.02%	29.36%	45.58%
Increase in Health	77.13%	60.16%	59.06%	15.33%

Appendix B: LULC

Table B1.

Landcover classification data acquired from satellite imagery analysis

Class	Area (km ²) in 1995	Area (km ²) in 2024
Woodland	29,379	16,862
Bushland	14,480	19,862
Shrubland	8,138	9,476
Grassland	5,146	7,951
Bare Area	4,663	9,407
Cropland	1,780	1,631
Water	599	771

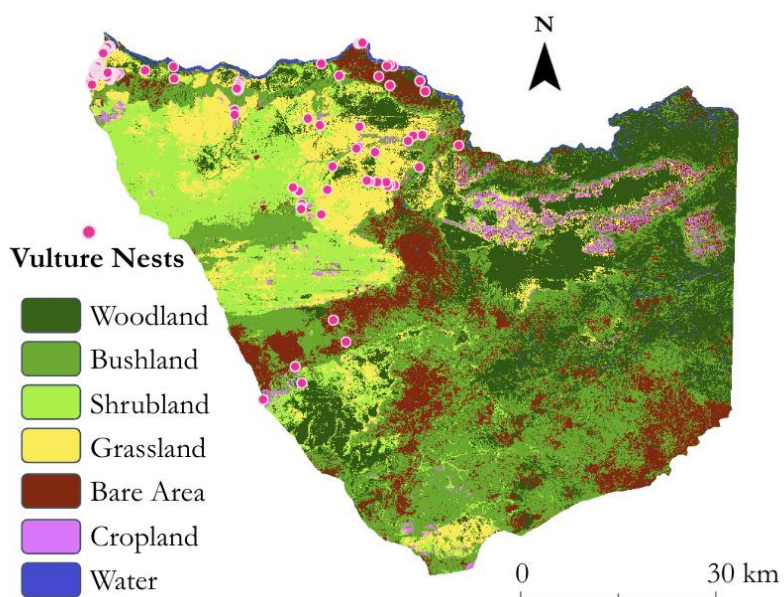


Figure B1. Landcover classification and vulture nesting sites from 2024