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RESEARCH ARTICLE

# Archival Aerial Photographs of Africa: Present Potential and Imagining a Machine-Learning Future

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## Abstract

Archival aerial photographs are a unique but underused and potentially game-changing source to study twentieth-century environmental and climate change dynamics. While satellite imagery with comparable high resolution appeared only in the early twenty-first century, archival aerial imagery with native sub-1-meter resolution became ubiquitous in the 1940s. Archival aerial photography therefore quadruples the time depth of high-resolution analysis to eighty years, allowing for a more reliable identification of structural trends. Moreover, the greater time-depth brings into focus the Great Acceleration that started in the 1940s, and virtually in real time. The article uses a human manual analysis of a sample from two time series (1943 and 1971) of archival photographs of the Oshikango area of Namibia (see Figure 1) to demonstrate how aerial photography complements conventional datasets. Namibia was one of the first places in colonial Africa where what subsequently became the standard protocol for "aerial mapping" was used and for which the imagery and the "flight plans" have survived. The standard protocol makes the imagery compatible with any archival aerial photography from the 1940s to 1990s and the flight plans contain key information to identify, interpret, and combine the individual photographs into orthomosaics. Although the use of manual analysis of aerial photography is not new, unlocking the full explanatory potential of high-resolution mass data requires machine reading and analysis. Current machine reading methods, however, are based on the pixel method, which identifies such features as farms, water holes, and trees only as low-resolution pixel aggregates. In contrast, the object method of machine analysis, combined with Geographical Information Systems (GIS) technology to unlock the sub-1-meter native resolution of historical aerial photography, renders visible individual trees and other features, including their precise location and size, allowing for the dimensions of trees and other features to be measured between different time series of images. The interrelationships between different features in the environment can thus be assessed more precisely in space and over time, for example comparing tree growth and surface water sources. A major challenge is that the object method used for high resolution geospatial imagery cannot


**Figure 1.** Northern Namibia with Oshikango marked. Source: ESRI Maps.

be easily applied to monochromatic archival aerial photography because it has been designed for analyzing multispectral satellite imagery. As discussed in the article, using the manual sample as a training data set for an experimental machine-learning protocol demonstrates proof of concept for automatically extracting such features as farms, water holes and trees as individual objects from archival aerial photography. This increases the time depth of available high-resolution land use, environmental, and climate data from 2000 back to the 1940s and provides a base line for the Great Acceleration and brings the massive changes from the 1940s through the 1990s in focus as captured in aerial photography.

**Keywords:** Archival aerial photographs; Environmental history; Machine learning; Namibian history

## Introduction

Widely used for military reconnaissance since the 1910s, and for map making from the 1930s and 1940s onward, archival aerial photography quadruples the time depth of the availability of high-resolution geospatial mass data. The black and white aerial photographs offer superb detail at a sub-1-meter resolution, which means that the pixels in the image register objects with a diameter of less than 1 meter across, contiguous territorial coverage, and the overlapping individual photos in each series provide a 3D view through a stereoscope. The level of detail visible on the images significantly improves

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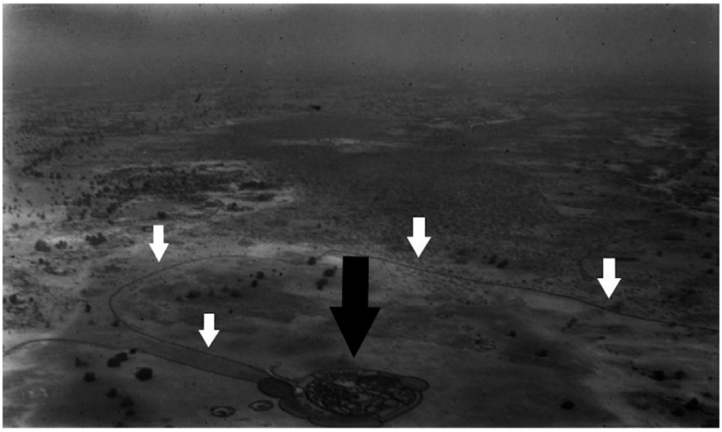

**Figure 2.** An oblique aerial photo from the 1920s depicting a large circular homestead (probably King Ipumbu of Uukwambi's) marked by a black arrow. The smaller white arrows point to the fenced outer boundary of the farm, enclosing the homesteads, the fields, livestock enclosures, the fallows and large fruit trees. Source: C.H.L. Hahn Collection, Namibian National Archives (henceforth NAN).

the ability to identify the dynamics of, and the trends in, for example, environmental, climate, ecological, economic, and demographic change.[1] The high-resolution imagery that the archival aerial photos offered could only be matched by the standard geospatial satellite imagery at the end of the twentieth century. As a result, small buildings, cars, and graves can be readily discerned, and changes in the density of, for example, trees between different time series of images help diagnose deforestation or reforestation (see Figure 2).[2]

Manually extracted sample data from archival aerial photos can be used as a training set for deep learning and machine reading the expansive collections worldwide, complementing other research methodologies and data sets to offer a more complete and longer-term analysis of the direction, causality, and impact of environmental and climate change.

[1] For examples of various uses, see Adrian Fox, Allison Cook, and Andrew Cziferksy, "Using Historic Aerial Photographs for Measuring Change on the Antarctica Peninsula," in *Landscapes through the Lens: Aerial Photographs and Historic Environment*, ed. David C. Cowley, Robin A. Standring, and Matthew J. Abicht (Oxford: Oxbow, 2010), 143–154 and Jessica L. Morgan, Sarah E. Gergel, and Nicholas C. Coops, "Aerial Photography: A Rapidly Evolving Tool for Ecological Management," *BioScience*, 60, no. 1 (2010): 47–59.

[2] For an example of people visible on archival aerial photos, see Daniel Uziel, "The Holocaust from Above: Auschwitz Imagery and Beyond," in Cowley et al., *Landscapes*, 267–280. For graves, see Matthew J. Abicht, "Using Wartime Aerial Photographs to Locate Lost Grave Sites," in Cowley et al., *Landscapes*, 263–266. For cars, see Cathy Stoerz, "US7GR LOC 349 3041: One Saturday Afternoon on the Home Front," in Cowley et al., *Landscapes*, 247–252.

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## Archival Aerial Photography

Archival aerial photos are an infrequently used source for environmental and climate history, although the technology has been used widely for military reconnaissance and archaeology since the First World War and for global mapping since the Second World War.[3] Archival (or historic) aerial photos are vertical or oblique analogue images taken from an airborne platform. The images are pan- or monochromatic, that is, they are rendered in black and white using grayscales. The images may be preserved as negatives in the form of glass plates or film, or as positive paper prints. The photographs are not georeferenced, and only part of the worldwide holdings in archives, libraries, government offices, the military, and private firms have been digitized. The US National Archive alone has 35 million aerial photos dating from 1918 to 2021. The commercial firm Aerofilms' collection boasts 1.26 million negatives of the UK dating from 1919 to 2006. Various French archives hold over 340,000 images covering France from the 1920s onward; the Alegoria project through digitization and processing has made 75,000 of them readily available.[4]

From the 1950s onward virtually every country and territory has been systematically and comprehensively photographed on a national scale through what amounted to a visual, bird's-eye-view decennial census. Some territories have been partially photographed since the First World War or the 1930s while the 1940s saw an explosion of aerial imagery coverage related to the Second World War and the Cold War. Although most countries' collections partially or fully cover their national territories, some countries, including the US, Russia, the UK, and France, created transnational collections of aerial images as colonial powers or because of their roles in the Second World War and the Cold War.[5]

The major advantages of archival aerial photography are the superb detail it offers at a native sub-1-meter resolution and the time depth of the available

[3] On the history of aerial photography, see, for example, Roy Conyers Nesbit, *Eyes of the RAF: A History of Photo-Reconnaissance* (Phoenix Mill, UK: Allen Sutton, 1998 [1996]); David C. Cowley, Robin A. Standring, and Matthew J. Abicht, eds., *Landscapes through the Lens: Aerial Photographs and Historic Environment* (Oxford: Oxbow, 2010); Martyn Barber, *A History of Aerial Photography and Archaeology: Mata Hari's Glass Eye and Other Stories* (Swindon: English Heritage, 2011); Jeanne Haffner, *The View from Above: The Science of Social Space* (Boston, MA: MIT Press, 2013); Birger Stichelbaut and David Cowley, eds., *Conflict Landscapes and Archaeology from Above* (Farnham, UK: Ashgate, 2016); and Caren Kaplan, *Aerial Aftermaths: Wartime from Above* (Durham, NC: Duke University Press, 2018).

[4] https://www.archives.gov/research/cartographic/aerial-photography; https://rcahmw.gov.uk/discover/aerofilms/; and http://alegoria.ign.fr/sites/default/files/22.01.28_ALEGORIA_collections_presentation.pdf.

[5] See, for example, David C. Cowley, Robin A. Standring, and Matthew J. Abicht, "Landscapes Through the Lens: An Introduction," in Cowley et al., *Landscapes*, 1–6 (US and UK); Jolanta Kijowska, Andrzej Kijowski, and Wlodzimierz Raczkowski, "Politics and Landscape Change in Poland: c. 1940–2000," in *Landscapes*, 155–166 (Poland); David Kennedy and Robert Bewley, "Archives and Aerial Imagery in Jordan: Rescuing the Archaeology of Greater Ammam from Rapid Urban Sprawl," in Cowley et al., *Landscapes*, 193–206 (Jordan); Giuseppe Ceraudo and Elizabeth J. Sheperd, "Italian Aerial Photographic Archives: Holdings and Case Studies," in Cowley et al., *Landscapes*, 237–246 (Italy). Colonial powers during and after the Second World War used aerial photography in their colonies (and beyond) and during the Cold War clandestinely photographed other countries' territories, see, for example, Nesbit, *Eyes of the RAF*, 127–129, 140–142, 231, 241, 272, 274, and 280–294.

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imagery. Multispectral satellite imagery – which captures four spectrums of light (including infrared) – has been the main source for geospatial analysis to assess, for example, climate change, deforestation, and urbanization, offers neither the high-resolution detail nor the time-depth of the mass data of archival aerial imagery. Multispectral satellite imagery with systematic global coverage only attained sub-1-meter resolution in the early 2000s. The multispectral imagery available before the late 1980s is either low resolution LANDSAT with 15–79 meters resolution, or, for CORONA, medium to high resolution of 3–12 meters.[6] The highest resolution versions of CORONA and GAMBIT register features of a minimum width of 2 meters and 1.2 meters respectively. SPOT-4 and SPOT-5 images, which were introduced in 1986 and 2002, respectively had a resolution of 10 and 2.5 meters. Multispectral satellite imagery only attained the high-resolution imagery of 1 meter or less of archival aerial photography in the twenty-first century, with the advent of IKONOS (2000), QUICKBIRD (2002), and GEOEYE (2008).[7]

The limited twenty-year time-frame available for higher resolution geospatial satellite data complicates the ability to distinguish structural changes from short-term conjunctures. Trends will only become more reliably identifiable with an additional forty to sixty years of comparable high-resolution data. In addition, the sheer magnitude of the resulting mass data sets to analyze to refine climate modeling is only as good as the historical data upon which they ultimately depend.

Extending the time depth by using archival aerial photography adds a critical 1940s baseline for assessing the impact of the Great Acceleration, the massive post-Second World War global transformation.[8] An additional 60 years of data would permit the Great Acceleration to be observed almost in real historical time, and as far back as the 1930s, depending on the aerial photography coverage of the territory. The archival aerial photo data sets depict post-Second World War recovery in Europe and the subsequent postwar explosion of industrialization, population growth, and urbanization. The 1930s and early 1940s constitute key baselines in terms of the levels of industrialization of manufacturing and agriculture, energy regimes (bringing the "transition" from coal to oil and nuclear into the equation), and mining and other forms of natural resource extraction in both the Global North and South.[9]

[6] The resolution of SPOT and other satellite images used in the late 1980s to assess land-use changes in Crete was too low because farmers' fields were often smaller than the pixels; see O. Rackham, "Woodland Ecology in Recent and Historic Aerial Photography," *Photogrammetric Record* 14, no. 80 (1992): 227–239.

[7] See Martin J. F. Fowler, "Satellite Imagery and Archaeology," in Cowley et al., *Landscapes*, 99–110.

[8] See J. R. McNeill and Peter Engelke, *The Great Acceleration: An Environmental History of the Anthropocene since 1945* (Cambridge, MA: Belknap Press, 2014).

[9] For example, Rackham noted in 1992 that the post-Second World War changes in England's forests can only be documented through aerial photos because the impact of deforestation (and reforestation) in the 1940s–1960s is little documented in other sources, see Rackham, "Woodland Ecology." On archival aerial photos as a source to assess post-Second World War deforestation, see Weixi Zhou, Ganlin Huang, Steward, T. A. Pickett, M. L. Cadenasso, "90 Years of Forest Cover Change in an Urbanizing Watershed: Spatial and Temporal Dynamics," *Landscape Ecology* 26 (2011): 645–659, doi:10.1007/s10980-011-9589-z.

## Archival Aerial Photography in the Global South: Ethiopia and Namibia

In the Global South, the 1940s–1960s marked a rapid transformation in industrial manufacturing, agriculture, and resource extraction driven by economic modernization and Western industrial expansion and well as explosive population growth. The Second World War saw the rapid expansion of southern Africa's economy. Mining, manufacturing, and agricultural production boomed during the war, increasing the demand for African labor from the region, especially from Namibia. Colonial "Ovamboland" (modern north-central Namibia) was the main source of African labor from Namibia and recruitment from the area soared from 4,000 laborers in 1938, to 6,500 in 1942, and 9,500 in 1948. Between 1949 and 1954, annual recruitment from Ovamboland involved 20 percent of all men from the area. Moreover, the laborers served increasingly longer contracts and engaged in multiple sequential contracts during the period, and since each individual recruit served a longer contract (18 months was common), male absenteeism may have been as high as 30 percent.[10]

Whereas Europe as a major theatre of war is well covered by archival aerial photography, such data is rare for sub-Saharan Africa, making it difficult to assemble a continent-wide 1940s baseline to assess the subsequent impact of the Great Acceleration. Partial exceptions include Ethiopia, with aerial photo coverage for 1935 to 1941, and Namibia, with a time series from 1943. Italian invaders produced 34,000 aerial photographs dating from the 1935 planning phase and ending with the defeat of their occupation forces in 1941. The Ethiopian images have been successfully used as a baseline to assess environmental change (land use, forest cover, infrastructure) during and after the war, but they only provide scattered coverage of relatively small fragments of territory. In addition, although the images have been digitized and integrated into a digital online archive, their use and interpretation remain challenging because they do not cover larger contiguous areas. Moreover, the pilots did not follow the operating procedures for aerial photography that became the standard during the Second World War. Not only were the flight paths followed by the pilots in Ethiopia and the usual overlap between adjacent strips of photographs irregular but the pilots also did not maintain a constant altitude during the flight, which makes the photos difficult to compare. Finally, no flight plans exist for the missions. Flight plans indicate the precise flight paths followed for taking the photographs, as well as the altitude at which the images were taken, and the plans typically provide information about the specific lens used. Without the metadata from the flight plans, the exact scale of each image is very difficult to determine, complicating assembling the individual photographs together to create orthomosaics. Orthomosaics are compilations of georeferenced photos, that is, photos that

[10] On South Africa's rapid war-time industrialization, see H. J. Martin and N. Orpen, *South Africa at War: Military and Industrial Organisation and Operations in Connection with the Conduct of the War, 1939–1945* (Cape Town: Purnell, 1979); Jill Nattrass, *The South African Economy, Its Growth and Change* (Cape Town: Oxford University Press, 1981), 212–221, and L. Thompson, *A History of South Africa* (New Haven: Yale University Press, 1990), 177–179. For the figures, see Emmanuel Kreike, "Recreating Eden: Agro-Ecological Change, Food Security and Environmental Diversity in Southern Angola and Northern Namibia, 1890-1960" (PhD dissertation, Yale University, 1996), 215, table 6.5 and 227–228.

have been georeferenced or matched to "real-world" GIS coordinates. Despite the challenges, a team of European and Ethiopian researchers successfully used the 1935–1941 series of photos to create orthomosaics and even did 3D historical landscape modeling of woody vegetation and hydraulic features in wartime Ethiopia. Moreover, some of the photo extraction and analysis was successfully automated.[11]

The Namibian 1943 series of aerial photographs covers a 10-mile-wide *contiguous* strip along the entire 250-mile-long Namibian-Angolan border of colonial Ovamboland; the negatives *and* the flight plans have been preserved, and the survey used what subsequently became the standard protocol for aerial mapping (with linear flight paths and overlapping imagery to facilitate stereo viewing). Namibia at the time was a League of Nations territory administered by South Africa. It appears that South African pilots flew the missions as a means of retraining them from bomber and other crew specializations to photo reconnaissance and new planes. Their month-long mission in Ovamboland was closely supported by the local colonial administration, which maintained a dirt landing strip at the administration's headquarters at Ondangwa in addition to preparing several improvised emergency landing strips along the border, including one at Oshikango. C. H. L. Hahn, the Native Commissioner of Ovamboland, was himself a committed amateur photographer and an early strong proponent of the use of South African military airpower. During his long tenure in Ovamboland, Hahn repeatedly called in live bombing demonstrations to intimidate indigenous rulers.[12] The September 1943 mission proved difficult (one of the planes and its pilot went missing for several days) and the exercise was hindered by heavy smoke caused by the on-farm burning of vegetation and debris that preceded the preparation of fields on the eve of the cropping season.[13] Because of these conditions, and because the mission took place early in the retraining process, flight paths were not always straight. Flight plans show the survey planes' altitude as well as providing other key metadata, including camera lens used. Moreover, all the individual photos were numbered individually and sequentially, and their positions were marked on the flight plans.

Although the quality of the images (contact prints from the preserved negative film) is much lower than more recent series of images, the 1943 imagery serves as an excellent baseline to compare with subsequent series on a sub-1-meter scale. Although not perfectly, the 1943 Namibian mission used the same standard protocol that is used for postwar aerial photography across the globe by air forces, national survey organizations, and private contractors. Thus, a 1972/1973 series for north-central Namibia offers an excellent comparison to assess land use and environmental changes. The 1970s series provides information about land use, environment, vegetation, settlement, and infrastructure just

[11] Jan Nyssen et al., "Online Digital Archive of Aerial Photographs of Ethiopia," *Geoscience Data Journal* 9 (2022): 3–36, doi:10.1002/gdj3.115.

[12] P. Hayes, "Vision and Violence: Photographies of War in Southern Angola and Northern Namibia," *Kronos* 27 (2001): 133–157.

[13] National Archives of Namibia (NAN), Native Commissioner of Ovamboland (NAO), 21, f. 11/1 (xvi), Quarterly Report Ovamboland, July–September 1943.

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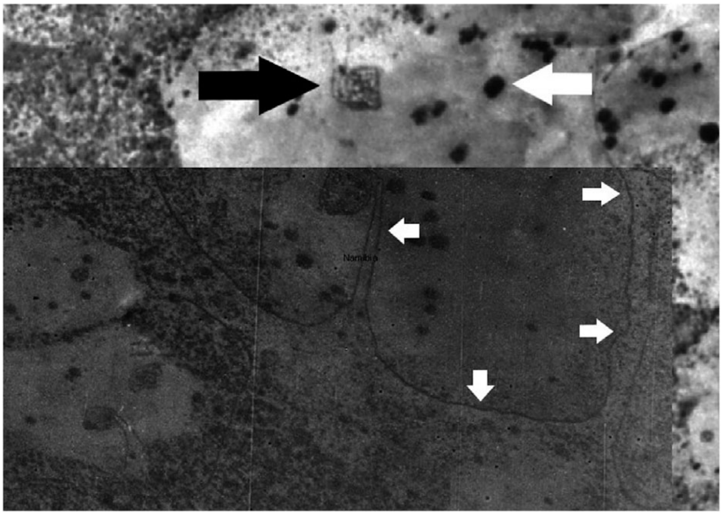


**Figure 3.** Composite of a 1943 aerial photo and a 1973 image showing the farm plot boundaries visible as a line consisting of branches heaped on top of one another (indicated by the small white arrows). The black arrow marks a homestead consisting of various homes, roofs, and granaries enclosed by a circular palisade constructed from wooden poles. The large white arrow points to the large round crown of a fruit tree in the fields. Source original photos: National Geodesic Service, Government of the Republic of Namibia (henceforth GRN)

before the intensification of the liberation war in northern Namibia. The area subsequently was severely impacted by war and population displacement from the mid 1970s to the late 1980s. Comparing the 1943 and 1970s series of aerial photographs therefore brackets the impact of the Great Acceleration in northern Namibia before it is skewed by the impact of mass conflict (see Figure 3).[14]

As was the case in Namibia, territories in other colonies and countries were photographed in sections, the aerial surveys were planned, and the images were archived through flight plans that provided key information on the routes, patterns, and altitudes flown by the planes, the type of camera and lens used, and the date and time the photos were taken. Aerial photography across the globe and throughout the period followed the same protocol, making the images highly comparable across time and space. The photos served to create maps at different scales, including high-resolution 1:20,000 or 1:10,000 maps that were used by the military and census takers and show even minor features that facilitate navigation, including, for example, local dirt roads, trails, paths, streams, and high-tension electricity lines. Before the high-resolution satellite images became available, the detailed maps derived from aerial photography

[14] In fact, an upsurge of violence may have been an explanation for the mission to have been commenced in 1971 but only having been completed in 1972. On the environmental impact of the liberation war in Namibia, see Emmanuel Kreike, "War and the Environmental Effects of Displacement in Southern Africa (1970s–1990s)," in *African Environment and Development: Rhetoric, Programs, Realities*, ed. William G. Moseley and B. Ikubolajeh Logan (Aldershot: Ashgate, 2003), 89–110.

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were used by the military to understand the local terrain, and to plot advance routes and targets for artillery fire. Aerial photography continues to be used as a survey method but, since the 1990s, the photos are taken in digital format. The enormous collections of aerial photos pre-dating the 1990s typically are available only in analogue form and preserved as large-size negatives or contact prints. Both the negatives and the paper prints are highly vulnerable; the former because of chemical leaching and the latter through shrinkage.[15]

Archival aerial photos are often preserved by special government bureaus, for example geodesic services or ordinance survey offices. In the US and in some western European countries, series from the 1960s, 1970s, and 1980s often are available in digitized format and can be downloaded for free or for a fee from government and commercial websites. In many countries, however, negatives and prints gather dust, deteriorate, and are seldom used. Short-staffed and under-resourced archives and libraries can lose track of entire series and, in some cases, given the fragility of the medium, the images are lost forever.[16] The negatives of the 1943 aerial photographs series discussed in the above, for example, were preserved virtually intact in the storerooms of the Namibian Geodesic Service. But the 1943 series did not appear in its inventories and was therefore effectively "lost" until the author encountered documents in the National Archives of Namibia that identified and provided the flight plan reference numbers.

Although frequently executed by international commercial firms, aerial photography is usually organized at the state level. Individual series and photos are taken over a period of several weeks, and like Google Earth imagery, the photos consequently do not represent one single moment in time. There is also substantial variation in shading because the photos are taken at different times of the day resulting in different shade lengths for consecutive photos within each series. Tall objects – for example, trees – that are photographed earlier in the morning and later in the afternoon, create longer shadows. Shades can thus be used to infer shape and height. When the density of the objects creating the shade is high, however, it is often impossible to distinguish the imprint of the objects themselves and their shades, to distinguish the shades of different objects, or to identify objects that are shaded by others.[17] Finally, while aerial photos are taken according to a specific protocol accepted worldwide, the timing

[15] First World War aerial photographs survive as glass plate negatives or paper prints, see Birger Stichelbaut, Wouter Gheyle, and Jean Bourgeois, "Great War Aerial Photographs: The Imperial War Museum's Box Collection," in Cowley et al., *Landscapes*, 225–236.

[16] After the Second World War, large collections were culled, including allied collections and the captured German aerial photographs. Of the latter, only an estimated 20 percent were preserved; see Abicht, "Using Wartime Aerial Photographs." Even in well-preserved collections, finding images of specific locations is often complicated. The UK's The Aerial Reconnaissance Archives (TARA) holds 15 million images for Europe, but many are not georeferenced, and the collection is not readily searchable, see Cowley et al., "Landscapes through the Lens: An Introduction."

[17] See Vander Luis de Souza Freitas, Barbara Maximino da Fonseca Reis, and Antonio Maria Garcia Tommaselli, "Automatic Shadow Detection in Aerial and Terrestrial Images," *Boletim de Ciências Geodésicas* 23, no. 4 (2017): 1–11, https://doi.org/10.1590/S1982-21702017000400038; and Daniel Rodrigues dos Santos, Quintino Dalmolin, Marcos Aurélio Basso, "Detecção Automática de Sombras

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for when they are taken depends on local circumstances, including the needs of national governments, and the local weather conditions. Generally, the aerial photos were taken during the season with the least cloud cover.

As with every data source, archival aerial photos reflect and contain biases. First and foremost, the images are a representation of reality, not reality itself. They reduce the world to grayscales, with very specific perspectives. The vertical bird's-eye view marks most of the archival aerial photography: the image is taken from a 90-degree angle from the flight path of the airborne platform, resulting in a flat, two-dimensional image, like that of a modern map. Stereoscopic imaging introduces a 3D view that, however, exists in the human eye and mind only, that is, it cannot be projected without human intervention. Oblique imagery (taken at a less than 90-degree angle), offers depth to the image and is more easily recognized by the human eye, but is much rarer in archival aerial photography collections because it was used for specific purposes only. Aerial photos are taking for surveillance purposes, for reconnaissance/spying, to identify military targets and assess the impact of bombing (and natural disasters), map-making, and are first and foremost instruments of state, colonial, and imperial control. Yet, the airborne vertical gaze is not all-seeing because cloud cover, shade, vegetation, buildings, camouflage, and resolution can obscure objects, especially people who are virtually absent to the naked lens.[18]

The article highlights how using a sample of two sets of archival aerial photos (from 1943 and 1972) adds value in terms of the quantity and quality of data and analysis. Available written and, to a lesser extent, oral information is qualitative and is produced for ruling elites by experts about subject people. It is spotty, with uncertainty about how representative the data is for a region or a period. Namibian colonial archives privilege the perspective of "outsiders" (colonial officials, settlers, missionaries, experts) and are shaped by racial and other prejudices. Often, historians must read between the lines of colonial documents or read them against the grain. Oral history offers insider perspectives, but interviewees mix different layers of pasts and presents and the observers' views with hearsay.

In raw form, that is as individual analogue greyscale images, aerial photographs offer representations of the past environment from a bird's-eye perspective, portraying a landscape in lines and shapes. As regular photographs they offer an alternative, visual representation of a past moment, created for very specific purposes often imbued with power relations. Aerial photographs, like maps, are and were expressions and means of domination, making environments legible to the colonizer by aiming to reduce a complex world to a standard pattern. Aerial photographs in Namibia as elsewhere, like maps, surveys and

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em Imagens de Alta Resolução," *Boletim de Ciências Geodésicas* 12, no. 1 (2006): 87–99, https://www.redalyc.org/pdf/3939/393937698006.pdf.

18 Kaplan, *Aerial Aftermaths*, 1–30 and 138–179; Haffner, *The View from Above*, 7–53; Mark Dorrian, "The Aerial Image: Vertigo, Transparency and Miniaturization," *Parallax* 15, no. 4 (2009): 83–93, doi:10.1080/13534640903208958. On the history of the God's Eye global view, see Denis Cosgrove, *Apollo's Eye: A Cartographic Genealogy of the Earth in the Western Imagination* (Baltimore: Johns Hopkins University Press, 2001).

censii, were and are tools of governing and rule.[19] Linking aerial photographs to one another and to a "real world" coordinate system allows for the creation of a new archive of quantifiable spatial data: trees, farms, wells can be counted, precisely located, and measured, but of course in the process, the analysis reproduces and at some levels multiplies the biases inherent in the medium.[20]

Aerial photographs require a lot of processing before their potential can be fully exploited. Only after archival aerial photos are georeferenced (that is, the images are linked to "real world" x, y coordinates through GIS technology), and orthorectified (correcting geometric distortions), their high resolution facilitates identifying, counting, and measuring dwellings, granaries, fences, fields, and even trees. A major bottleneck is that because the processing and analysis of archival aerial photos must be done manually, it is extremely labor intensive. The development of methods to automate the data extraction are key to being able to process the large quantities of available images (most of them are, for example, not georeferenced) to unlock the full potential of the underused source.[21] With machine reading, changes can be assessed in quantitative and statistical terms across different time series of images.

Despite the laboriousness of manual extraction, archival aerial photographs have been successfully used as a historical source, especially for urban and forest history and in archaeology. In the field of archaeology, aerial photos primarily were used to identify prehistorical or historic sites, but there is an increasing focus on analyzing entire landscapes. Images from the 1930s and 1940s are particularly revealing for identifying historic sites or landscapes because they predate the impact of the Second World War and the enormous changes in the landscape that occurred from the 1950s and 1960s onward because of industrial agriculture and urbanization. Archaeology and many historical studies use qualitative analysis to identify visible changes between one or more images from one time series with one or two images from another time series, but they

[19] Keith P. Feldman, "Empire's Verticality: The Af/Pak Frontier, Visual Culture, and Racialization from Above," *Comparative American Studies: An International Journal* 9, no. 4 (2011): 325–341, doi:10.1179/147757011X13045212814529; Hayes, "Vision and Violence"; Dorrian, "The Aerial Image." On state simplification, see James C. Scott, *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed* (New Haven: Yale University Press, 1998). On photography and the "colonial gaze" in Namibia, see Wolfram Hartmann, Jeremy Silvester, and Patricia Hayes, eds., *The Colonising Camera: Photographs in the Making of Namibian History* (Athens: Ohio University Press, 1999).

[20] Historical data are often qualitative, scattered, imprecise, and incomplete, but digital, GIS, and computational methods presume high precision. The encoding required for reformatting qualitative historical data into precise GIS coordinates, for example, may make them more "scientifically" precise, which is an artifact of the reformatting itself. See, for example, Anne K. Knowles, ed., *Placing History: How Maps, Spatial Data, and GIS Are Changing Historical Scholarship* (Redlands: ESRI Press, 2008), 1–25 and 219–233; and Ian N. Gregory and Paul S. Ell, *Historical GIS: Technologies, Methodologies, and Scholarship* (Cambridge: Cambridge University Press, 2007).

[21] For an example of (near)automated detection of feature correspondences between temporal series of archival aerial images, see Lulin Zhang, Ewelina Rupnik, and Marc Pierrot-Deseilligny, "Feature Matching for Multi-Epoch Historical Aerial Images," *ISPRS Journal of Photogrammetry and Remote Sensing* 182 (2021): 176–189, www.elsevier.com/locate/isprsjprs; and S. Giordano, A. Le Bris, and C. Mallet, "Towards Automatic Georeferencing of Archival Aerial Photogrammetric Surveys," *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 4, no. 2 (2018): 105–112.

do not systematically compare time series of images to extract and analyze quantitative changes.[22] Urban settlements, with their linear and large features, and large, contiguous, forest-covered areas are more easily detected on aerial photos. Even then, manual extraction of data from aerial photos remains laborious and requires expert knowledge of the given environment. Moreover, interpretation is subject to the analyst's human bias, and ground truthing with historical images is typically not possible. Ground truthing is based on a real-time and on-the-ground survey to assess what features visible on the images correspond to what features observable in the environment captured in the imagery. Finally, while archival aerial photos are panchromatic in black and white with only grayscales, 1990s digital aerial photos and satellite images are multispectral greatly facilitating data extraction in the case of the latter.[23] As a result of the challenges to prepare the pre-1990s analogue archival aerial photographs, with few exceptions they have been used either as illustrations, or to study very small areas. Even when larger areas were covered, only samples were taken because it was too costly to manually assess the entire area covered by the aerial photos.[24]

## Digitizing and Machine Reading Archival Aerial Photography

Digital machine-reading analysis by the pixel method, that is, a process of automatically attributing an exclusive value to each pixel in an image, can assess total coverage in an image by an aggregate feature class, for example "forest." But it does not map the trees that the forest is composed of as individual objects of analysis. The 1935–41 Ethiopian War aerial photography project successfully used automated feature extraction employing the pixel method to map a "woody vegetation" feature class that grouped all pixels with tree cover in a single,

[22] For archaeology and aerial photography, see Cowley et al., *Landscapes*; Barber, *History of Aerial Photography*; and Stichelbaut, *Conflict Landscapes*. Very common is the use of limited numbers of photos and qualitative analysis of urban change or changes in regions; see, for example, Kenneth Hudson, *Industrial History from the Air* (Cambridge: Cambridge University Press, 1984) and Terence C. Cartwright, *Birds Eye Wartime: Leicestershire, 1939–1945* (Wigstone: TCC Publications, 2002).

[23] One method developed is to effectively try to transform mono-spectral archival aerial photos in multispectral images by colorization through machine learning; see, for example, Q. Poterek et al., "Revealing Long-term Physiological Trajectories of Grasslands from B&W Aerial Photographs," Author's version of an article published at ISPRS 2020. The authenticated version is available online at: https://doi.org/10.5194/isprs-annals-V-3-2020-549-2020.

[24] Fairhead and Leach used a small sample of aerial photos from different dates to support their argument that deforestation in West Africa was a myth; see J. Fairhead and M. Leach, *Misreading the African Landscape: Society and Ecology in a Forest-Savanna Mosaic* (Cambridge: Cambridge University Press, 1996). For other examples, see F. Gerard et al., "Land Cover Change in Europe between 1950 and 2000," *Progress in Physical Geography: Earth and Environment* 34 (2010): 183–205; Kaplan, *Aerial Aftermaths*, 8; L. A. Roman et al., "Growing Canopy on a College Campus: Understanding Urban Forest Change through Archival Records and Aerial Photography," *Environmental Management* 60 (2017): 1042–1061, https://doi.org/10.1007/s00267-017-0934-0; and Jeffrey T. Walton, David J. Nowak, and Eric J. Greenfield, "Assessing Urban Forest Canopy Cover Using Airborne or Satellite Imagery," *Arboriculture & Urban Forestry* 34, no. 6 (2008): 334–340. On using selected samples to make a detailed forest cover assessment, see Zhou et al., "90 Years of Forest Cover Change."

undifferentiated, and aggregated category.[25] As a result, it is not possible to, for example, trace the history of individual trees in the environment or to assess their relation to other feature class objects that link them to the same space and time. The pixel method consequently is a less satisfactory approach with high-resolution (1 meter or less) imagery because it renders invisible individual objects.[26] The object focused method "reads" such features as trees, farms, and wells through image processing thereby holding more promise in unlocking the potential of high resolution archival aerial photos through machine-learning technology.[27] Comparing individual trees across different time series of aerial photos allows for an assessment of actual tree loss and gain. In some cases, the sub-1-meter resolution even facilitates the identification of specific tree species. as is the case in north-central Namibia.

Algorithms and methods that have proved highly successful to machine read multispectral remote sensing and multispectral digital aerial photography, however, cannot simply be applied to interpreting archival aerial photos, which only work in the single grayscale visible light spectrum. In contrast, multispectral satellite imagery uses three to four spectral bands beyond visible light, including infrared, but although it provides more diverse information, its spatial resolution is typically lower (4-meter resolution for IKONOS and 2.44-meter for Quickbird). For these reasons, machine reading panchromatic images, including pre-1999 archival aerial photos to date has proven challenging. Machine deep-learning approaches are yielding promising results via the pixel method, but less so via the object method, thus frustrating an ability to identify such individual

[25] Nyssen et al., "Online Digital Archive."

[26] See Morgan, "Aerial Photography"; and Jessica L. Morgan and Sarah E. Gergel, "Automated Analysis of Aerial Photographs and Potential for Historic Forest Mapping," *Canadian Journal Forest Research* 43 (2013): 699–710, doi.org/10.1139/cjfr-2012-0492. Bolles and Forman used a semi-automated pixel approach to quantify correlation between land use and degradation during the 1930s dustbowl; Kasey C. Bolles and Steven L. Forman, "Evaluating Landscape Degradation Along Climatic Gradients During the 1930s Dust Bowl Drought from Panchromatic Historical Aerial Photographs, United States Great Plains," *Frontiers in Earth Science* 6, no. 153 (2018): 1–22, www.frontiersin.org.

[27] For high-resolution satellite imagery object-based machine-learning classifiers have proved far more effective than pixel-based classification; see Yuguo Qian et al., "Comparing Machine Learning Classifiers for Object-Based Land Cover Classification Using Very High Resolution Imagery," *Remote Sensing* 7 (2015): 153–168, doi:10.3390/rs70100153; and W. Zhou and A. Troy, "An Object-oriented Approach for Analysing and Characterizing Urban Landscape at the Parcel Level," *International Journal of Remote Sensing* 29, no. 11 (2008): 3119–3135, doi:10.1080/01431160701469065. For promising applications to historical images, see Rémi Ratajczak et al., "Automatic Land Cover Reconstruction from Historical Aerial Images: An Evaluation of Features Extraction and Classification Algorithms," IEEE Transactions on Image Processing 28, no. 7 (2019): 3357–3371, doi:10.1109/TIP.2019.2896492; and Nicholus Mboga et al., "Fully Convolutional Networks for Land Cover Classification from Historical Panchromatic Aerial Photographs," *ISPRS Journal of Photogrammetry and Remote Sensing* 167 (2020): 385-395. See also I. Cacciari and G. F. Pocobelli, "The Contribution of Artificial Intelligence to Aerial Photointerpretation of Archaeological Sites: A Comparison Between Traditional and Machine Learning Methods," *Archeologia e Calcolatori* 32, no. 1 (2021): 81–98, doi 10.19282/ac.32.1.2021.05. Using an unsupervised machine-learning application, they found that black and white aerial photos were much more readable for cartographic restitution (in this case for the automatic identification of graves) than color images.

objects as trees and water holes.[28] These challenges need to be overcome to extract comparable detailed information from the archival aerial photographs as from the post-2000 high resolution satellite imagery that is critical in studying land use, environmental, and climate change today.

## Reading Archival Photographs from North-Central Namibia

North-central Namibia, known in the colonial era as Ovamboland, comprises the modern four administrative regions of Ohangwena, Oshikoto, Omusati, and Oshana. Namibia was formally colonized by Germany in the 1880s (although it never occupied Ovamboland), becoming a South African administered territory for the League of Nations territory after the First World War and for the UN after the Second World War. South Africa annexed it in the 1980s, until it gained its independence in 1990 after a protracted liberation war. The region was the principal source of African labor for the settler farms and mines of colonial Namibia from the early 1910s onward and from the early 1940s to the early 1970s also for Apartheid South Africa's mines, industries, and settler farms.[29]

[28] On digital machine reading, through the pixel method, see Andrew T. Hudak and Carol A. Wessman, "Textural Analysis of Historical Aerial Photography to Characterize Woody Plant Encroachment in South African," *Remote Sensing of Environment* 66, no. 3 (1998): 317–330, doi:10.1016/S0034-4257(98)00078-9; Ronen Kadmon and Ruthie Harari-Kremer, "Studying Long-Term Vegetation Dynamics Using Digital Processing of Historical Aerial Photographs," *Remote Sensing of Environment* 68, no. 2 (1999): 164–176 (PII S0034-4257(98)00109-6); Ratajczak et al., "Automatic Land Cover Reconstruction"; Nicholus Mboga et al., "Domain Adaptation for Semantic Segmentation of Historical Panchromatic Orthomosaics in Central Africa," *ISPRS International Journal of Geo-Information* 10, no. 523 (2021): 1–19, doi.org/10.3390/ijgi10080523; Khai Zhang et al., "Panchromatic and Multi-spectral Image Fusion for Remote Sensing and Earth Observation: Concepts, Taxonomy, Literature Review, Evaluation Methodologies and Challenges Ahead," *Information Fusion* 93 (2023): 227–242. On an example of using deep learning and machine extraction of stone walls from archival aerial imagery, see Ji Won Suh, William B. Ouimet, and Samantha Dow, "Reconstructing and Identifying Historic Land Use in Northeastern United States Using Anthropogenic Landforms and Deep Learning," *Applied Geography* 161 (2023): 103–121, doi:10.1016/j.apgeog.2023.103121. For a successful object application with larger objects (landslide debris fields) using modern panchromatic imagery (i. e., post-1997 imagery that is more consistent in quality of the images than older native-born analogue aerial photography), see Tapas R. Martha et al., "Object-Oriented Analysis of Multi-Temporal Panchromatic Images for Creation of Historical Landslide Inventories," *ISPRS Journal of Photogrammetry and Remote Sensing* 67 (2012): 105–119, doi:org/10.1016/j-isprsjprs.2011.11.004.

[29] On the history of the region, see E. M. Loeb, *In Feudal Africa* (Bloomington: Indiana University Research Center in Folklore, 1962); R. J. B. Moorsom, "Underdevelopment, Contract Labour, and Worker Consciousness in Namibia, 1915–1972," *Journal of Southern African Studies* 4, no. 1 (1977): 52–87; R. J. Gordon, "Variations in Migration Rates: The Ovambo Case," *Journal of Southern African Studies* 3, no. 3 (1978): 261–294; W. G. Clarence-Smith, *Slaves, Peasants and Capitalism in Southern Angola, 1840–1926* (Cambridge: Cambridge University Press, 1979); M. Hiltunen, *Witchcraft and Sorcery in Ovambo* (Helsinki: Finnish Anthropological Society, 1986); P. H. Katjavivi, *A History of Resistance in Namibia* (London: James Currey, 1988); H. Siiskonen, *Trade and Economic Change in Ovamboland, 1850–1906* (Helsinki: SHS, 1990); F.-N. Williams, *Precolonial Communities of Southwestern Africa: A History of the Owambo Kingdoms, 1600–1920* (Windhoek: National Archives, 1991); P. Hayes, "A History of the Ovambo of Namibia," (PhD dissertation, Cambridge University, 1992); M. Eirola, *The Ovambogefahr: The Ovamboland Reservation in the Making: Political Responses of the Kingdom of Ondonga to the German Colonial*

The historical environment of north-central Namibia has been studied extensively and in detail, making it an excellent case study for imagining past environments that can serve as a proxy for ground truthing.[30] Although north-central Namibia is a semi-arid environment, with only 400–600 mm (16–24 inches) of rainfall and a long May–October dry season, it historically has sustained half of colonial Namibia's population, and the area continues to be densely settled. Until the construction of a canal and pipeline system in the 1970s, local inhabitants were entirely dependent on harvesting the local rainfall and floodwaters from the north, which in favorable years reached north-central Namibia's Ovambo floodplain from Angola. The area has no permanent rivers or any other *natural* surface sources of water to sustain the population. Settlement in the region historically extends to the Kunene River only on the northwestern extremity. During the colonial era, the population relied on wells, water reservoirs, and in particular water holes (shallow wells that did not penetrate the impermeable subsoil layers) in the dry season. The scarcity of the dry season water sources dictated a dispersed settlement pattern of homesteads with abutting fields, grouped in villages. In the Ovambo floodplain in the center of the region, villages and farms were located on low dune-like features. Before the construction of all-weather roads from the 1960s onward, heavy rains and flooding during the rainy season isolated the villages from one another. Farmers fenced the fields to protect the staple millet and other crops from livestock during the growing season. During the dry season, herdsmen drove the cattle to remote cattle posts as water, grazing and browse were scarce in the villages. Large trees, including fig, marula, and palm trees were concentrated on-farm and were an important source of nutrition. The prominence of these environmental characteristics significantly contributes to assessing the data generated by machine reading the monochromatic images from the series of archival

Power, 1884–1910 *(Rovaneimi: Ponjois-Suomen Historiallinen Yhdistys, 1992); R. L. Monteiro,* Os Ambós de Angola antes da Independencia *(Lisbon: Universidade Técnica de Lisboa, 1994); P. Hayes et al., eds.,* Namibia under South African Rule: Mobility and Containment, 1915–1945 *(Oxford: James Currey, 1998); V. Notkola and H. Siiskkonen,* Fertility, Mortality, and Migration in Sub-Saharan Africa: The Case of Ovamboland in North Namibia, 1925–90 *(Basingstoke: Macmillan, 2000); M. McKittrick,* To Dwell Secure: Generation, Christianity, and Colonialism in Ovamboland *(Portsmouth: Heinemann, 2002); E. Kreike,* Re-Creating Eden: Land Use, Environment, and Society in Southern Angola and Northern Namibia *(Portsmouth: Heinemann, 2004).*

[30] On the environmental history of Ovamboland, see S. Soini, "Agriculture in Northern Namibia: Owambo and Kawango, 1965–1970," *Journal of the Scientific Agricultural Society of Finland* 53, no. 3 (1981): 168–209; M. Seely and A. Marsh, eds., *Oshanas: Sustaining People, Environment, and Development in Central Ovambo* ([Windhoek], 1992); A. Erkkilä and H. Siiskonen, *Forestry in Namibia, 1850–1990* (Joensuu: University of Joensuu, 1992); J. Mendelsohn, S. El Obeid, and C. Roberts, *A Profile of North-central Namibia* (Gamsberg Macmillan: Windhoek, 2000); A. Erkkilä, "Living on the Land: Change in Forest Cover in North-Central Namibia, 1943–1996" (PhD dissertation, University of Joensuu, 2001); Kreike, *Re-Creating Eden*; E. Kreike, *Deforestation and Reforestation in Namibia: The Global Consequences of Local Contradictions* (Leiden: Brill, 2010); E. Kreike, *Environmental Infrastructure in African History: Examining the Myth of Natural Resource Management in Namibia* (Cambridge: Cambridge University Press, 2013).

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**Figure 4.** A detail from the 1943 series. The black arrow indicates Oshikango, which in 1943 consisted of little more than the office and home of the Assistant Native Commissioner of Ovamboland. The 1943 series is of poor quality relative to the 1972 series, with scratches on the negative. Source original photos: National Geodesic Service, GRN.

aerial photographs. Ovamboland's farms, fences, fields, water holes, livestock enclosures, and trees, amongst other features, are visible in the high-resolution imagery (see Figure 4).

North-central Namibia experienced droughts and famine conditions during the twentieth century, most intensely during the first two decades of the century, during the late 1920s, during the 1940s, and during the 1980s and early 1990s. Recent studies suggest the region is highly vulnerable to climate change.[31] Historically, the region's society and environment demonstrated remarkable resilience and adaptability in the face of environmental, political, and economic challenges, including two protracted periods of war, from 1900 to 1920 (the colonial conquest era) and again from 1968 to 1989 (during the liberation war). The highly flexible, dynamic, and diversified land use system that local societies sustained consisted of an elaborate environmental

[31] Republic of Namibia, *First Adaptation Communication: Namibia's Climate Change Adaptation Communication to the UNFCCC* (Windhoek: Ministry of Environment, Forestry and Tourism, 2021); M. N. Angula and M. B. Kaundjua, "The Changing Climate and Human Vulnerability in North-Central Namibia," *Jamba: Journal of Disaster Risk Studies* 8, no. 2 (2016): 200, doi:10.4102/jamba.v8i2.200; and Andrew J. Newsham and David S. G. Thomas, "Knowing, Farming and Climate Change Adaptation in North-Central Namibia," *Global Environmental Change* 21, no. 2 (2011): 761–770, doi:10.1016/j.gloenvcha.2010.12.003.

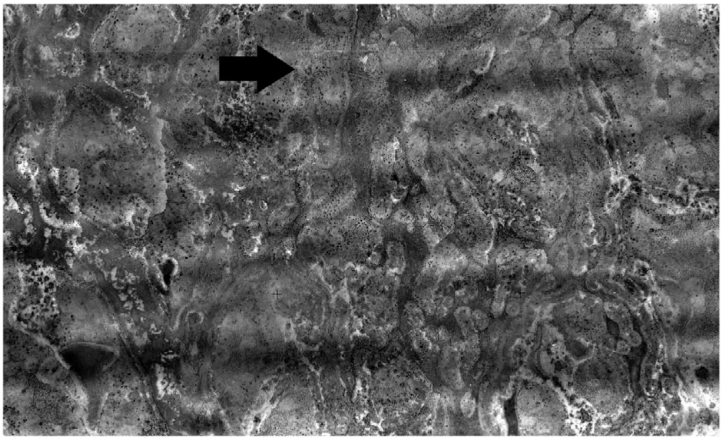

**Figure 5.** Landscape of northern Namibia with homestead (indicated with black arrow) surrounded by millet fields and shadowed by trees. The white arrow identifies a large marula (Sclerocarya birrea) that towers over the landscape. On vertical aerial photos the trees are visible as very dark circles. Source Photo: author.

infrastructure that was constantly repaired, reconstructed, and reimagined to sustain a dense population. The environmental infrastructure relied on a deep and ongoing investment of labor, knowledge, and other resources, not in the least the capital investments earned though migrant labor and remittances from beyond the region. Until the mid 1970s, the region was a main source of agricultural and mine labor for both the farms and mines of Namibia and of South Africa (see Figure 5).

The increased male absenteeism from their home villages and farms and the increased wages they earned had major impacts on land use and the environment. Male labor inputs in agriculture decreased, which negatively affected cattle management, while female labor input and management in agriculture increased. The former was partly compensated by increased earnings being invested in animal draft plowing. Overall, however, agricultural production did not increase: the dissemination of the plow during the 1940s and 1950s led to larger crop fields (and more land enclosure) but the increased weed competition resulted in decreased yields per unit of land. In addition, the plow allowed using the harder clayish soils of the region that had been challenging to work with hand-held hoes to be cultivated, but the low-lying clayish soils were more susceptible to flooding during the rainy season. Plowing also interfered with the raised-field pattern of cropping typically used in the floodplain environment of the region: it was difficult to create raised fields when plowing, which effectively exacerbated the risk of water-logging even on the higher ground where villages, farms, and fields were typically located. That the increased wages were invested in domestic animals (donkeys, cattle) also impacted land use and the environment in other ways. The increased availability to young men of cash and cattle and goods bought with wages allowed them to marry and acquire their own farms sooner. More young men and women left their parents' households earlier, depriving the latter

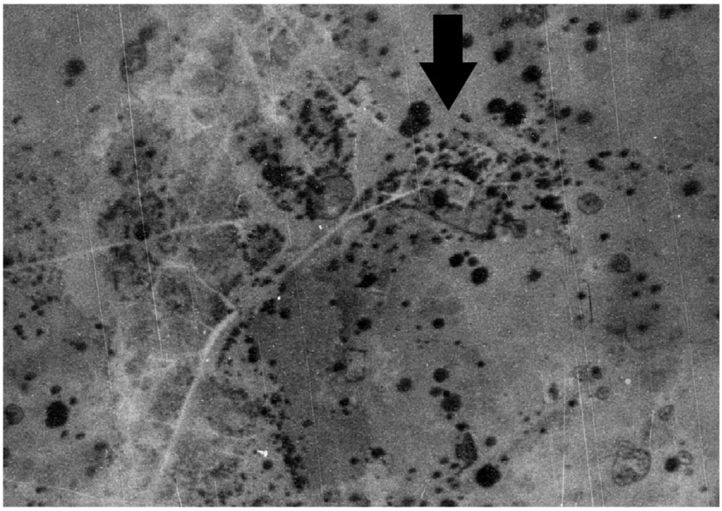

**Figure 6.** Oshikango is marked again by a black arrow and had by the early 1970s grown into a small administrative center. The rectangular feature in the center, indicated by the large white arrow with the black border, is a water reservoir ("dam" in South African parlance) to support the administrative center and the staff residences. The large white arrows indicate homesteads. The small blacklined white arrows indicate the dark round crowns of three large fruit trees (marula or birdplum). Source original photos: National Geodesic Service, GRN.

of labor and leading to a rapid expansion of settlement in the floodplain. Parents subdivided farms and young couples settled in new, less suitable lands that were less fertile, covered with bush or trees, or more prone to flooding, making agriculture more precarious and increasing vulnerability to the effects of climate change. The increase in domestic livestock, in particular the massive importation of donkeys as draft animals in the 1940s and 1950s (for plowing and carts and wagons) impacted the availability of grazing, forage, and water even as time investment in livestock management decreased. In addition, the 1940s and subsequent years saw rapid population growth due to in-migration from neighboring Angola and natural increase (see Figure 6).[32]

The dynamic intensity of local land-use practices explains why the region successfully absorbed tens of thousands of migrants and refugees from southern Angola during the first half of the twentieth century and doubled the population of north-central Namibia by the 1940s. The migrants and refugees settled overwhelmingly in a narrow strip south of the border, which by the early 1900s had only been sparsely settled. The massive migration in the 1920s and 1930s triggered a famine and dramatic expressions of concern by missionaries and some colonial officers about overpopulation, deforestation, and desertification, misgivings that reemerged in the 1950s and 1960s and again in the 1980s and 1990s. The 1943 series is particularly important because it depicts the narrow strip of land south of the

[32] Kreike, *Re-Creating Eden*, 81–176 and Kreike, *Deforestation and Reforestation in Namibia*, 127–137.

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Angolan-Namibia border where the bulk of the refugees and migrants from Angola had settled.[33] Unravelling this story based on the 1943 and subsequent series of imagery may be particularly salient in the face of the actual and projected massive war and climate-induced migrations of the twenty-first century worldwide.

Colonial (and postcolonial) officials and experts from the 1950s onwards interpreted the environmental changes they observed in terms of overpopulation, deforestation, desertification, soil erosion, and overgrazing. The specter of environmental disaster triggered radical colonial interventions, including the violent imposition of restrictions on the movement and importation of livestock, and cattle culling, leading to increased unrest and resistance, which was a factor in the eruption of organized armed resistance in the late 1960s.[34]

The extent to which the resilience and adaptability observed in the twentieth century will hold in the face of twenty-first century climate change is an urgent and compelling question. Analyzing environmental and land use changes from 1943 to 2023 by combining the data that can be derived from the last two decades of high-resolution satellite data with the six decades deep archival aerial photography may provide answers and suggest strategies to mitigate or adapt to climate change.

## Archival Aerial Photography: Gaining a Bird's-Eye Perspective

The argument is based on the comparative analysis of a selection of archival aerial photos of north-central Namibia ("Ovamboland") from 1943 and 1972. Each of the 1,400 photos used was scanned manually at 1,200 dpi. The individual photos were roughly georeferenced and cut and pasted to fit them together into a seamless collage or orthomosaic after correction for color and geometric distortions.[35] Next, the author extracted a series of features from a sample of the larger orthomosaic depicting an 8 × 12 km rectangle covering 9,600 hectare (ha) around the town of Oshikango from each of the time series. These samples served to demonstrate the type of data that could be extracted and served as a training set for machine learning (see Figure 7).

A systematic analysis of the features that can be extracted from archival aerial photos adds detailed quantitative and spatial data. For example, whereas archival reports and oral histories may reveal that water holes were historically the main source of water in an area, aerial photography can tell how many water

[33] The year 1943 is two decades after the big migration of the late 1920s; Kreike, *Recreating Eden*, 23–46 and 101–128.

[34] Kreike, *Deforestation and Reforestation in Namibia*, 35–112 and 139–160; P. Hayes, " 'Cocky Hahn' and the 'Black Venus': The Making of a Native Commissioner in South West Africa, 1915–1946," in *Gendered Colonialism in African History*, ed. N. R. Hunt, T. P. Liu, and J. Quataert (Oxford: Blackwell, 1997), 42–70.

[35] Tsering Wangyal Shawa, "Creating Orthomosaic Images from Historical Aerial Photographs," *e-Perimetron: International Web Journal on Sciences and Technologies Affined to History of Cartography and Maps*, 18, no. 1 (2023): 1–15. In general, see Holger Heisig and Jean-Luc Simmen, "Re-Engineering the Past: Countrywide Georeferencing of Archival Aerial Imagery" (University of Salzburg Master's thesis submitted within the UNIGIS MSc programme, Interfaculty Department of Geoinformatics – Z_GIS, 2020. Manuscript to be submitted to *Remote Sensing or ISPRS International Journal of Geo-Information*).

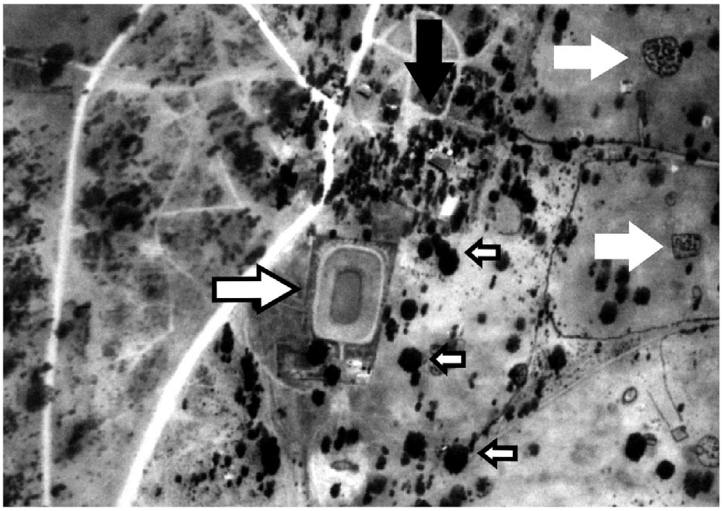

**Figure 7.** The orthomosaic of the 1943 series covers an 8 by 12 km (9,600 ha) area including the location of the modern border town of Oshikango (indicated by the black arrow). The orthomosaic extends from Engela in the west to Onengali-East and Okatale in the east. Source original photos: National Geodesic Service, GRN.

holes were in use in each area and when, how large they were, and where they were in the landscape, providing the information in both statistical and visual formats. The article offers an analysis of the data that can be extracted from the sample orthomosaic to illustrate the argument.

The main feature classes created for the sample analysis discussed here are water holes, homesteads, enclosed farm plots, and trees.

## *Water holes*

Although water holes were critical sources of household water consumption during the long dry season, written historical data about water holes is scarce and scattered. An early 1900s description claims they were 3–4 meters deep and yielded 30–40 liters in 24 hours. A 1966 colonial report stated that water holes were low-yielding, and that one water hole could sustain at best only a few households throughout the dry season. In a 1977 sample, only eight out of thirty-three homesteads scheduled for removal because of a construction project contained a water hole or well. The 1991 census found that 60 percent of the households in north-central Namibia relied on "wells" (which mainly seems to have referred to water holes).[36] Oral histories highlight that water holes were low-yielding, and that, serving as the main – if not the only – source of water during the dry season, they were often shared between neighboring households. To save

[36] Kreike, *Recreating Eden*, 15–25, 101–110, 129–154 and Kreike, *Environmental Infrastructure*, 103–116.

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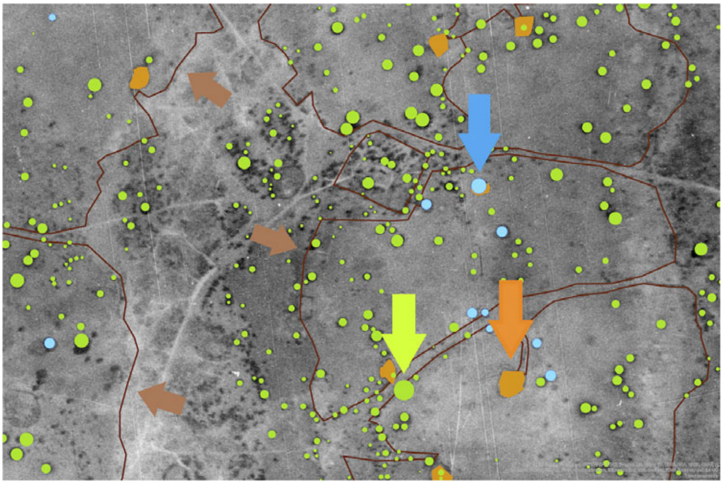

**Figure 8.** Extracted features on a detail of the 1943 series. The orange arrow points to the shapefile showing the form and size of a homestead (in orange). The blue arrow identifies a water hole which consists of a shallow excavation that collects water stored in the sandy soil (the water holes are indicated as blue dots). Because of their limited yield, the water holes were fenced; on aerial photos they appear as a circle (the fence) with a dark shape in the middle representing the shadow cast by the excavation. The brown lines (highlighted by small brown arrows) indicate farm boundaries consisting of a pole frame with brushwood and branches stashed against and on top of it. The fences had to be renewed annually and are usually clearly visible in the aerial photos (they are usually about 1.5 meters wide). The fences served to keep livestock out of the crop fields during the agricultural season. The green dots indicate trees, marking the shape and the size of the crowns visible in the images (green arrow as example). Source original photos: National Geodesic Service, GRN.

water, cattle were herded away from the villages for the duration of the dry season, saving the reserves stored in the water holes for human consumption.[37]

Manually extracting features from the aerial photos offers detailed quantitative and visual data to enhance the scarce qualitative data from archival documents and oral histories. The 1943, 8 × 12 km (9,600 ha) orthomosaic depicts 337 fenced water holes that supported a total of 482 homesteads. The 1973 orthomosaic contained 510 fenced water holes shared by 814 homesteads. The existence of many more homesteads than water holes supports the view that the water holes were shared between households. The mean size of the fenced areas encompassing the water holes in 1972 was 25 percent larger than in 1943 (0.020 ha in 1973 compared to 0.015 ha in 1943) suggesting that the water holes had been increased in size over time. Perhaps the water holes had been widened to increase the yield. The images also show that the water holes were often clustered and that they were located on the edges of homesteads or farm boundaries (see Figure 8).

[37] On water harvesting and water holes, see Kreike, *Environmental Infrastructure*, 103–116.

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## Homesteads

Single household homesteads consisted of round homes with wooden walls and thatch roofs, roofs without walls (kitchens), granaries, and different areas fenced in with a large pole palisade. Pole palisades also separated individual living and communal quarters within the homesteads, giving them the appearance of mazes. The palisaded homesteads originally functioned as a defense against human raiders and animal predators. The outer palisade or stockade was 2–3 meters high and could reach a diameter of 30–40 meters. The homesteads and their palisades are clearly visible on the aerial photos.

There are few detailed descriptions of the homesteads available through archival documents and oral history in terms of their size and composition. Regular photos available for the area are equally spotty and qualitative in nature and lack information on location and dating and are limited to elite homesteads.

The aerial photos offer precisely what is lacking in the qualitative sources. In 1943, the 9,600 ha depicted in the 9 × 12 km orthomosaic near Oshikango contained 482 homesteads. About half of the homesteads in the 1943 images belonged to three villages: Oshikango, Onaminda, and Odibo. A 1938 census counted 69 households and 466 people in Oshikango; 103 households and 595 people in Onaminda and 25 households and 173 people in Odibo. The villages belonged to the colonial district of Oukwanyama, which in 1938 had 8,370 homesteads and 52,580 inhabitants compared to 6,689 homesteads and a population of 41,215 in 1933. The 482 homesteads identified on the orthomosaic thus constituted 4–5 percent of all the homesteads on the district of Oukwanyama based on the 1938 statistics. The total population of colonial Ovamboland increased rapidly, from 107,000 in 1933, to 200,000 in 1951, and 618,000 in 1991.[38]

In 1972, the same orthomosaic counted 814 homesteads. Homestead density increased from one per 20 ha in 1943 to one per 11.8 ha in 1972, almost a doubling of the settlement density, reflecting the rapid population increase. The mean size of the surface enclosed by the palisaded homesteads decreased from 0.092 ha in 1943 (with 482 homesteads enclosing a total of 44 ha) to 0.07638 ha in 1972 (814 homesteads counting 62.2 ha). Thus, the mean size of the palisade enclosed homestead decreased by approximately 15 percent. The 1972 series images also show the layout of the homesteads in detail, and it is often possible to identify the intricate palisaded maze layout and to distinguish the individual roofs of homes, kitchens, and granaries. The lower quality of the 1943 images makes it sometimes impossible to identify such details (see Figure 9).

[38] Kreike, *Recreating Eden*, 104 and Kreike, *Deforestation*, 41.

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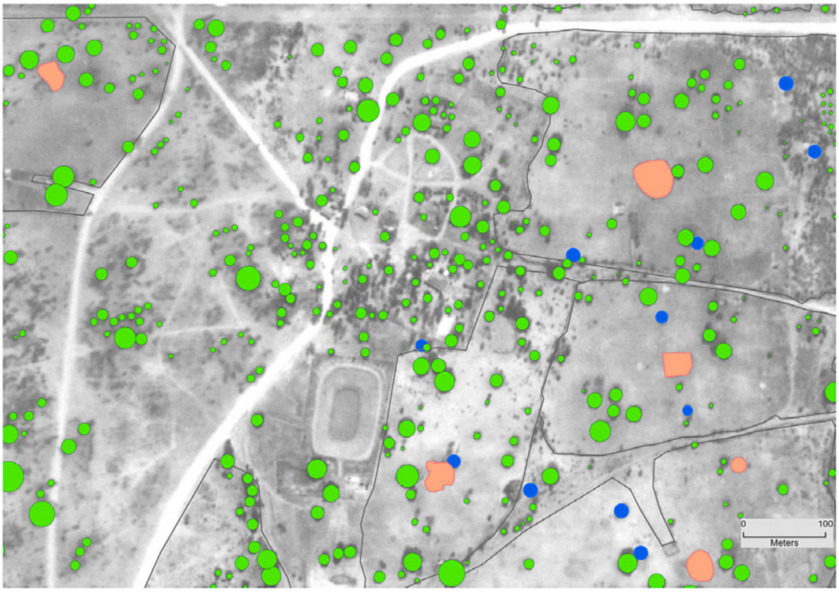


**Figure 9.** Detail from the 1972 orthomosaic near Oshikango (the Oshikango water reservoir or dam is visible in the center of the image as a rectangular feature). The irregular larger orange shapes represent the shape and size of homesteads based on the extent of the palisaded enclosure but excluding the palisaded cattle enclosures. The farm fences that encompass the homestead and fields as well as a fallow are indicated as dark lines. The green circles are trees (representing the shape and surface of the crowns as visible on the images) and the blue circles are water holes (also depicting their shape and surface area).

## *Fenced farm plots*

Statistics about the size of farm plots are scarce and suggest that the farm plots ranged from as small as 0.5 ha to 2–5 ha. Sometimes the scant figures refer to the entire farm plot, which was often marked by a fence that is visible in aerial photographs. Sometimes, however, the figures refer to the surface area under active cultivation within the larger farm plot, which usually included a bush fallow. As the aerial photos analysis confirms, it was common for two or more neighboring households to maintain a single fence around their combined farmlands. Maintaining the fences was exceptionally labor intensive as the long fences had to be repaired and renewed every year.[39]

In the 1943 series, the 9,600 ha orthomosaic contained 345 farm plots that enclosed 39,002,561.8 $m^2$ (3,900 ha), with a mean plot size of 11.3 ha. The 345 fenced lots, however, included 482 households with their own farm, thus the average plot size per household was closer to 8 ha. In 1972, the number of

[39] Kreike, *Environmental Infrastructure*, 71–92.

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fenced farm areas had increased to 513, enclosing an area of 4,496 ha and including a total of 814 homesteads. The mean size of a fenced plot, which often enclosed the land of more than one household, measured 8.76 ha, with an average plot size per household of 5.5 ha. In all cases, the aerial photos show that only a part of the plots was actively cultivated. Both the mean size of fence-enclosed farmlands and the individual average land holdings per household decreased between 1943 and 1972, with a dramatic decrease in the plot size per household of almost one third. Moreover, while in 1943, 40 percent of the area covered by the orthmosaic was enclosed by farmland, in 1972, more than half of the land had become enclosed by fences. Currently, the 1943 and 1972 orthomosaics are only approximately georeferenced. Once the georeferencing has been refined, the identification of the exact location of the old 1943 features will be possible on the 1972 images and we can assess, for example, if plot size of older (i.e., 1943) farms decreased overall, or if new farm plots identified on the 1972 orthomosaic were substantially smaller, causing the dramatic reduction in overall plot size.

### *Trees*

Erkkilä and Kreike have argued that past land used in north-central Namibia was marked not only by deforestation (because of clearing woody vegetation for fields and using wood for the construction of homes, palisades, and fences) but also by reforestation. Colonial officials identified the towering (fruit) trees that dominated the region as wild species and believed them to be the remnants of natural forest cover. Oral histories, however, strongly suggest that the real fan palm (*Hyphaene petersiana*), birdplum (*Berchemia discolor*), and marula (*Sclerocarya birrea*) were actively and passively propagated, with farmers seeding, transplanting, and selectively protecting seedlings. Erkkilä offered a detailed analysis based on manually interpreting a sample from the 1943 aerial photos series, highlighting their substantial potential as an innovative source. Working with a small sample of images from the Ohangwena area, Erkkilä used quantitative data to demonstrate that large trees increased in the center of the fenced farm plots between 1943 and 1996. Furthermore, by estimating the number of poles used in the palisades that he measured on the imagery, he concluded that local wood use was sustainable in the eastern part of north-central Namibia (see Figure 10).[40]

The analysis of the Oshikango orthomosaic sheds new light on these arguments. In 1943, the 345 areas enclosed by farm boundaries and occupied by 482 homesteads, contained 10,883 trees. The on-farm trees constituted a bit over half of the total of 20,339 tree-class features extracted from the 1943 orthomosaic. Off-farm trees, however, were likely undercounted, given individual tree crowns were more difficult to distinguish because of the denser off-farm vegetation. To compensate for the undercounting of off-farm trees, only large trees are included in the analysis below.

[40] Erkkilä, "Living on the Land" and Kreike, *Deforestation*.

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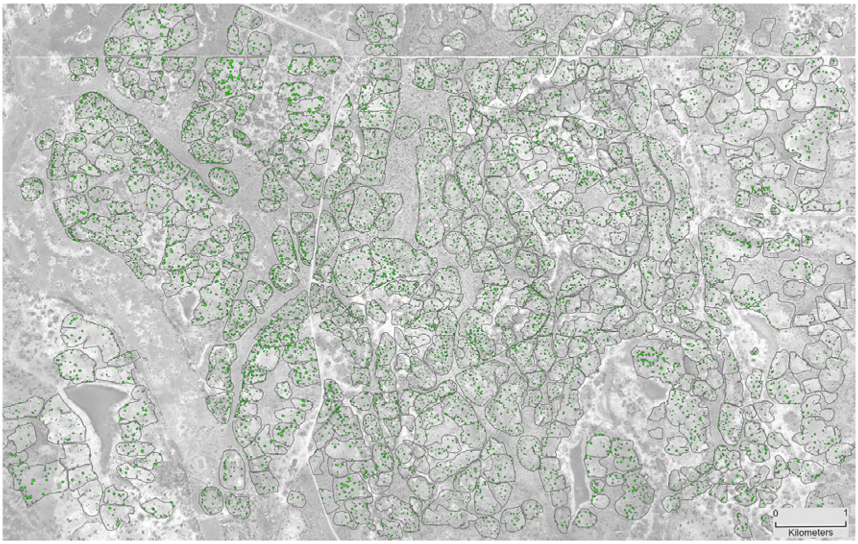


**Figure 10.** Farm boundaries of 482 plots (dark lines) and trees (green dots) in the sample orthomosaic. The image demonstrates a pattern visible throughout the entire 8 by 12 km orthomosaic: on-farm trees in 1972 tended to be larger trees and off-farm trees on average were smaller.

Of the on-farm trees (those located within the farm fences), 2,924 were large trees with crowns equal to or larger than 100 $m^2$ (0.01 ha). The combined crowns covered 550,876.4 $m^2$ (55 ha). Most of the larger-crowned trees are likely to have been either marula, birdplum, or fig (*Ficus spp.*) fruit trees. The real fan palm effectively is excluded from the large tree category because its crowns are smaller than 100 $m^2$ (see Figure 11).

In 1972, the 513 enclosed farmland plots occupied by 814 households contained 20,547 trees of the total of 35,392 trees that populated the entire 9,600 ha photomosaic (Figure 10). Of those, 7,433 trees had a crown size equal to or larger than 100 $m^2$ and shaded 1,751,949.7 $m^2$ (175 ha). On-farm, tree crown density of the largest trees compared to 1943 increased more than threefold (over 300 percent) even though the number of enclosed farm plots only grew by half (50 percent). Whereas in 1943, each of 345 enclosed farmlands counted on average 8–9 large trees each and each homestead had 7–8 large trees, in 1972, the average enclosed plot contained 14–15 large trees, with each homestead averaging 9 large trees. The quantitative analysis based on the orthomosaic thus strongly supports the argument for on-farm reforestation. Also noteworthy is that although the overall number and density of large trees increased markedly, the number of large trees per household increased less significantly over the same period. This finding raises questions about the overall access that households and individuals had to the fruit trees and the resources they offered. Again, after the georeferencing has been refined, it will be possible to assess if this was mainly a challenge to new farms established after 1943.

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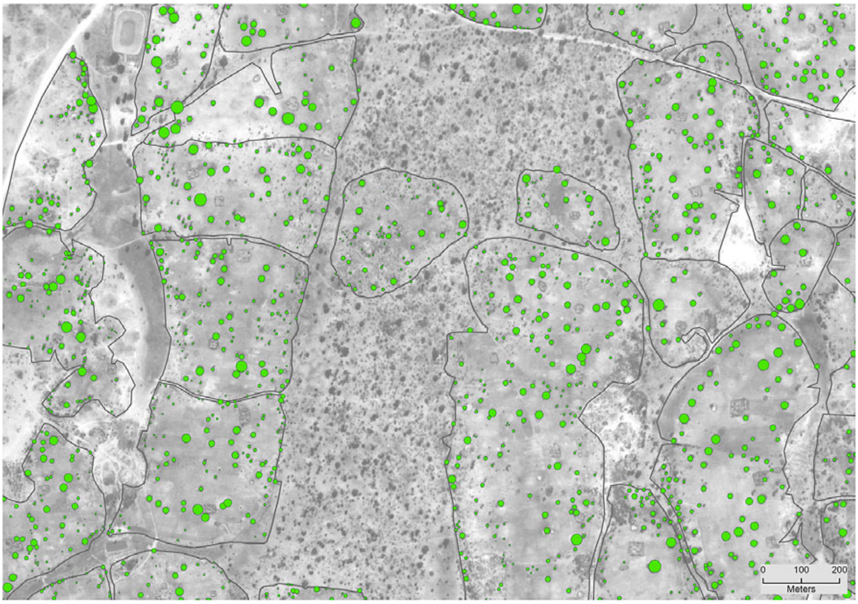


**Figure 11.** Detail from the 1972 orthomosaic that shows the boundaries of farm plots (dark lines) and the on-farm trees (green dots) that were extracted.

## Pixels and Objects

Manual extraction and analysis of archival aerial photos identifies individual waterholes, homesteads, farm plots, and trees. The pixel method of machine reading the imagery counts the total pixels of each category and only provides a rough spatial identification of the location of the aggregate features, that is, the areas with trees. In that sense, pixel method machine reading does not add significantly to the pre-2000s low-resolution satellite imagery that is available. In contrast, the object method of machine reading does full justice to the sub-meter accuracy of the archival aerial photos and can be more effectively combined with GIS to fully exploit the data-rich imagery. With the object method, archival aerial photographs can be exploited as data sets in the same way as post-2000 high resolution geospatial imagery. Little is known about dryland tree coverage in Africa, although the role of trees in climate mitigation is well established. Tucker, for example, used machine learning to extract data from 300,000 high-resolution satellite images, mapping 9.9 billion individual tree crowns over 3 $m^2$ in diameter across the width of the African continent in a zone between the equator and the Sahara to calculate, amongst others, carbon uptake.[41]

In the Namibian case, using the object method of machine learning and all available series of aerial photos and satellite imagery from 1943 to 2023,

[41] Compton Tucker et al., "Sub-Continental-Scale Carbon Stocks of Individual Trees in African Drylands," *Nature* 615 (2023): 80–86.

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individual trees could be followed through the eighty-year period. The 1943 sample orthomosaic counted at least 20,000 trees; upscaling that figure to the entire 4,000 $km^2$ area of Ovamboland would mean that approximately 800,000 trees can be followed for eighty years. For example, sample tree ring extraction from 2,023 individual trees identified in the 1943 mapping can provide data on tree growth and to calculate carbon storage and uptake. Tree rings and crown increase can be linked to rainfall data. Trunk growth can be correlated with crown increase extracted from the time series of imagery and provide a model for understanding the relationship between crown and trunk increase elsewhere in Namibia and Africa. For example, the marula tree (*Sclerocarya birrea*), a dominating feature in north-central Namibia's environment, is prevalent throughout the savannas of southern and eastern Africa, along with many other trees from the area, making the results valuable for research elsewhere.

Moreover, with the data on a range of individual features, including homesteads, crop fields, fallows, and water holes, the relationships between features can be assessed at multiple scales, from the level of individual farms to a neighborhood, to a village, a district, a country, a region, a continent, and even the global scale. Correlating tree growth with the presence and size of water holes and other data on surface water (the extent of surface flooding in a single time series of imagery is visible in the aerial photography), combined with rainfall data may reveal critical insights in the hydrology of the region. As the canal and pipeline system expanded from the 1970s onward, the use of water holes and other water harvesting technology declined. Archival aerial photography can help to ascertain how widespread the phenomenon was and assess if it is a factor in the reported increased incidence of flooding and water-logging in the region. Perhaps the precious local water supply previously harvested through water holes as a key household resource transformed into a climate threat?

## The Orthomosaic as a Deep-Learning Training Sample

The above analysis of the orthomosaic serves to highlight what archival aerial photos can add to more conventional sources and analysis. But the full potential of the tens of millions of historical aerial photos gathering dust in archives and libraries worldwide as a source for mass data can only be effectively unlocked if a set of algorithms is developed to facilitate machine extraction and image processing based on the object method rather than the currently available pixel method. Manual extraction and processing is too laborious. The pixel method of machine reading cannot map such individual features as trees and water holes and their shape, size, and location. An object method machine feature extraction and image processing of the underused archival aerial images would allow for a detailed analysis and visualization of environmental, climate, settlement, demographic, and land uses changes in north-central Namibia from the 1940s to the present, optimizing time depth to include a pre-Great Acceleration baseline and exploiting the native sub-1-meter resolution of the medium.

The data extracted from the 8 × 12 km Oshikango orthomosaic presented is serving as a training tool for deep (machine) learning neural networks. A first,

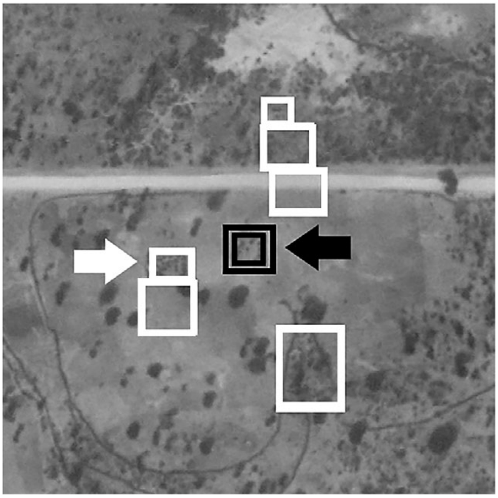

**Figure 12.** Machine-extracted homestead features.

preliminary experiment demonstrated that combined with off-the-shelf software, machine learning works: the algorithm used could extract individual features that it identified as "homesteads" based on the training data. The next step is to refine the extraction and to introduce spatial data to read the shape and the size of the selected features. Figure 12 shows how based on the training sample homestead feature (marked by the black box), the application identified other features as homesteads. The area indicated in the white box marked by the white arrow has been identified correctly as a homestead. The other white boxes are other features that are misidentified (see Figure 12).

Figure 13 highlights a correctly identified homestead in the training sample orthomosaic (the black box and black arrow) and a misidentified "other" feature (a cattle enclosure) marked with a white box and a white arrow. Of the 130 or so machine-extracted features, approximately 30 were homesteads, a lowish predictability rate of 20 per cent. It also missed about 30 homesteads, especially the ones that were not round in form or very large in size. It seemed to identify small round features encircled by dots (small tree crowns). This was a limited run with only the homesteads and although the predictability rate was low, it was promising for a first attempt because it identified all the features as individual objects.

## Conclusion

This article highlights the potential of extracting features from a 1943 and a 1972 series of archival aerial photos that were digitized, compiled, and georeferenced into an orthomosaic to assess environmental change in north-central Namibia. The use of this underutilized source adds new data sets over a much longer period,

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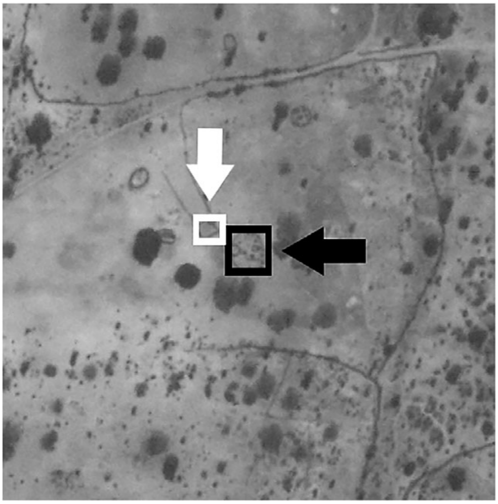

**Figure 13.** Correctly identified homestead in training sample.

providing a foundation for quantitative, statistical, spatial, and visual analysis that greatly enriches and enhances the data and analysis available through satellite imagery. The wealth of data of archival aerial photos, however, is also its biggest limitation because the sheer global coverage they provide and the massive data they hold makes wholesale manual extraction and processing impossible. The computer-assisted and machine-learning methods that have been used for the analysis of high-resolution satellite imagery based on a full color spectrum analysis cannot be applied to monochromatic grayscale aerial photos. In this article, manually extracted time series of aerial photography serve to illustrate their value as a training set for an object-based, machine deep-learning "proof of concept" trial. The experiment demonstrated that a training set can effectively facilitate machine learning, and thereby enable automatic feature extraction. Developing an algorithm through supervised deep learning can thus unlock the full potential of the massive collections of archival aerial photos that document the earth's landmass during the twentieth century and reveal its intricate dynamics in past, present, and future.

Unlocking the full potential of archival (or historical) aerial photography quadruples the time depth of high-resolution data that currently are available through modern satellite imagery, bringing into focus the Great Acceleration from it 1940s start to the present. In addition, machine-reading through the pixel method does not exploit the full resolution of archival aerial photo and only yields approximately located feature class aggregates (i.e., "forests"). The object method, however, maps such features as individual objects (i.e., trees). The article serves as a reminder of what the sub-1-meter resolution of archival aerial photography can offer and compares the pixel and object-based approaches to machine-reading panchromatic imagery. Moreover, it shows how using a manually prepared machine-learning data set is critical to developing additional

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machine-reading methods to use archival aerial photos to deepen our knowledge about the dynamics of environmental and climate change. Finally, the article reports on the result of an experiment with machine reading an orthomosaic based on the 1943 and 1972 series of north-central Namibian archival aerial imagery. The first run achieved a modest 20 percent reliability, showing that machine reading read only one out of every five manually extracted features correctly. But it did identify the features as individual objects and not as pixel aggregates denoting an undifferentiated forest class. Therefore, it offers proof-of-concept for the potential of deep-learning protocols for developing an object method of machine extraction and analysis that unlocks the potential of the massive collections of underused high-resolution of the tens of millions of archival aerial photos that linger in depositories across Africa and across the globe.

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