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Remote sensing-based fire frequency mapping in a savannah rangeland.

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Abstract

Burnt area mapping and fire frequency analysis were carried out in Hwange National Park, Zimbabwe. Hwange National Park typifies a savannah ecosystem which is semi-arid and fire-prone. This paper presents a geospatial analysis to quantify the spatial distribution and fire frequency from 2000 to 2006. Moderate Resolution Imaging Spectroradiometer (MODIS) images from 2000 to 2006 were obtained and classified for burnt area mapping. Linear pixel unmixing was used for image classification and subsequent mapping of burnt areas. The results showed that it was feasible to have discrimination of burnt areas and 'un-burnt' areas as well as generating a six year fire frequency map of the study area. Accuracy assessment of the classified images was carried out using field obtained information on fire occurrence to validate the classification results. An error matrix quantified accuracy of classified maps through producer's accuracy, user's accuracy and overall accuracy. High overall accuracy rates of appromately 96%, in turne, justify use of linear pixel unmixing in identifying and mapping burnt areas. Thus pixel unmixing offers a viable mapping tool for fire monitoring and management in protected areas.

1. Introduction

The increasing temperatures and decreasing precipitation, in Southern Africa's savannah region, will continue to impact heavily on its fire regime (Kusangaya et al., 2013, Pricope and Binford, 2012). These changes will in turn affect the ecology, structure, and function of the savannah ecosystem. In most cases, fires in these ecosystems occur as wild fires (Pricope and Binford, 2012). Fire is a significant factor in determining the ecology of savannahs, boreal forests, and tundra ecosystems (Dwyer et al., 1999). Fires on the African savannah burn large areas of vegetation annually (Dwyer et al., 2000) and this led to it being identified as one of the major threats causing the loss of forests in sub-Saharan Africa (Silva et al., 2003). On the other hand, wild fires play a critical role in ecosystem functioning such as offsetting plants and grass regeneration through providing ideal germination and growth conditions (Masocha et al., 2011). The fires, especially in the savannah biome, have led to Africa often being referred to as the “fire continent” (Navashni, 2003).

The savannah ecosystem covers approximately 50% of the land surface in Africa and is characterized by the coexistence of both grasses and trees (Scholes and Walker, 1993). Burning in the savannah, therefore, has regional and global impacts since fires emit large amounts of greenhouse gasses and aerosol particles (Andreae, 1997, Crutzen and Andreae, 1990) and can lead to changes in vegetation cover (Louppe et al., 1995). Frequent burning of the savannah is also thought to result in land degradation and loss of biodiversity (Masocha et al., 2011) e.g. through allowing invasion by alien invasive species. This calls for the development of an efficient and accurate system to map and monitor burnt areas caused by savannah fires. Although fire monitoring has been given priority by numerous international research organisations (Justice, 1994, Roy et al., 2005), in Zimbabwe biomass burning has continued to increase in the past decades (Tafengenyasha, 1997, Gambiza et al., 2005, Gandiwa and Kativu, 2009).

The causes of wild fires differ with ecosystems which are generally grouped into natural and human-induced ones. These fires are mainly due to lightning (natural) as well as intentionally set incendiary fires (human-induced) (Silva et al., 2003). Humans caused wild fires are mostly through agricultural land clearings, rangeland management, and burning of agricultural residues (Brivio et al., 1999). The global impact of fire on atmospheric chemistry, strong relationships with biogeochemical cycles and implications on climate change are now widely recognised (Goldammer, 1990, Levine, 1991, Crutzen and Goldammer, 1993, Levine, 1996). Vegetation fires account for roughly half of the atmospheric constituents of hydrocarbon, carbon monoxide, nitrogen oxides; all precursors of tropospheric ozone (Crutzen and Andreae, 1990). As a result fire information is useful in driving regional emission models, trace gas transport models, and meso-scale models of atmospheric chemistry (Dwyer et al., 1999).

In Hwange National Park, fire is a ubiquitous terrestrial disturbance factor mostly resulting from anthropogenic activities within or adjacent to the park (Tafengenyasha, 1997). Although Southern Africa experiences one of the worst biomass burning in the world (Dwyer et al., 1999), more research is still required on this environmental phenomenon since the impact of fires remain poorly addressed in fire ecology studies (Masocha et al., 2011), especially at local management levels. Different satellite image products have been used for mapping burnt areas. Examples include the Global Burn Scar (GLOBSCAR) (Simon et al., 2004), Global Burnt Area – 2000 initiative (GBA2000) (Tansey et al., 2004) and the MODIS burnt area product (Justice et al., 2002, Roy et al., 2002). The Global VGT burnt area product 2000 -2007 (L3JRC) is available globally on a daily basis and is based on SPOT Vegetation imagery (Tansey, 2007). Furthermore, long-term observations of active fires derived from space borne sensors are available. These include the Along-Track Scanning Radiometer (ATSR) night time fire product (Arino and Rosaz, 1999), the Visible and Infrared Scanner (VIRS) monthly fire product (Giglio et al., 2003), the Moderate Resolution Imaging Spectroradiometer (MODIS) global fire product (Justice et al., 2002), and the Geostationary Operational Environmental Satellite (GOES) Wildfire Automated Biomass Burning Algorithm (WF ABBA) fire product (Prins et al., 1998). Of these, the MODIS Fire Products are designed to provide information for both global change science and practical management applications (Justice et al., 2002, Kaufman et al., 1998). However, because of the global focus of most of these products, there are no adequate data on the regional occurrence, size distributions or trends in fire numbers or areas burnt annually that meet the information needs of policy and decision-makers (Frost, 1999) at local level such as park management. Hence the thrust of this study, to map and determine fire frequency in Hwange National Park, Zimbabwe at the regional level at which fire management is carried out.

2. Materials and Methods

2.1. Study area

Hwange National Park, founded in 1928, is situated in the North-West of Zimbabwe extending from 17°48′ South, 25° 15′ East to 19°52′ South and 26°42′ East. It is Zimbabwe's largest game park covering an area of approximately 14,600km^2. The park is bounded by Botswana in the West, Matetsi and Deka safari areas in the North, state forest land and farms in the North-east and Tsholotsho communal land in the South-East (Figure 1).

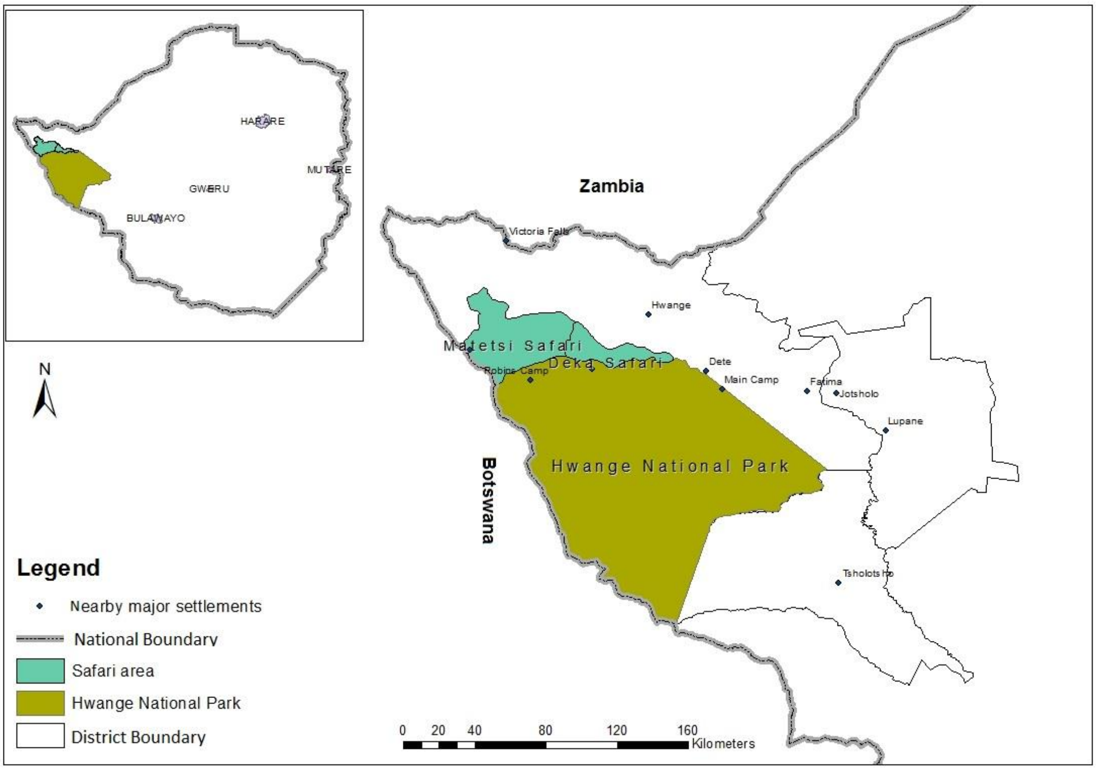

Figure 1: Location of Hwange National Park in Zimbabwe

Vegetation of the park comprises mixed woodlands and shrub lands of *Bairkiea plurijuga, Combretums, Acacias and Terminalia sericea* (Marion et al., 2006). Generally, the woodland vegetation of the park is dominated by *Baikiea plurijuga*, *Baphia massaiensis* and *Kalahari bauhinia*. However, in the north and north-west of the park mopane woodland (*Guibourtia coleosperma*) is more dominant (Cumming et al., 1997, Hyde et al., 2010). The park receives a mean annual rainfall of about 620mm and mean annual temperature range is 7°C-35°C. It is coolest between May to August while September to March are the warmest months. The dry season occurs in April through October and the wet season occurs from November to March. In the dry season, temperatures get as high as 33°C (in October) and this period coincides with fire occurrence in the park.

Currently, fire management and mitigation activities are highly dependent upon the knowledge and intuition of fire management personnel. Fire management and mitigation within the park is guided by the main fire policy of the Parks and Wildlife Authority of Zimbabwe. Within the park, establishment and maintenance of ‘fireguards’ is one of the main tools of fire control and prevention. These strategies are enshrined in the Parks and Wildlife Act of 1991 (Parks and Wildlife Act, 1991). Fire mitigation outside the park is enforced through the Forest Act of 1990 (Forest Act, 1990) and the Environmental Management Act of

2002 (Environmental Management Act, 2002). Both Acts regulate the burning and preventive measures used to supress and control the spread of wildfires.

2.2. Data

MODIS is a satellite sensor instrument mounted on NASA's Terra Earth Observing System (EOS AM) and Aqua Earth Observing System (EOS PM) satellites. Image bands 1 (620-670 nm) and 2 (841-876 nm) of MODIS with a spatial resolution of 250m (NASA, 2013) were used. These image bands were selected because MODIS’s multi-spectral capabilities in the visible and near-infrared regions and narrow spectral bands have an advantage of improved spatial resolution compared to National Oceanic and Atmospheric Administration (NOAA)’s Advanced Very High Resolution Radiometer (AVHRR), previously widely used for burnt area mapping. October images were selected, before the onset of the rainy season and which coincidentally marks the end of the fire season in Zimbabwe (Silva et al., 2003). As such the resultant burnt area maps were assumed to be representative of the burning that would have occurred during the whole fire season from May to October. Hence the estimated burnt areas derived from each of the satellite images were a good estimation of the spatial distribution of burnt areas for each year’s fire season. All the MODIS October images covering Hwange National Park for the years from 2000 to 2006 were subsequently processed for burnt area mapping.

2.3. Remote sensing

Traditional multispectral classification techniques are based on the spectral properties of different classes of interest and employ parametric classification algorithms based on Bayes' theorem which originates from probability theory. These techniques include the Maximum likelihood, Minimum Distance, Parallelepiped (Box), Minimum Mahalanobis Distance, ISODATA and the K-Means (Wang and Jia, 2009) classification methods. These algorithms lead to the assignment of each pixel to a single class thereby making assumptions of pure (Foody, 2002), discrete and mutually exclusive pixels (Congalton and Green, 2008) which in the real world do not exist. In coarser multispectral imagery, these assumptions are difficult to fulfil due to the presence of mixed pixels (Campbell, 1996, Wang and Jia, 2009). On the other hand, linear pixel unmixing has shown great promise in overcoming the identified shortcomings. Thus linear pixel unmixing was employed for this study.

2.3.1 Linear pixel unmixing

Spectral unmixing is a quantitative analysis procedure used to recognise constituent ground cover materials (or end members) and obtain their mixing proportions (or abundances) from a mixed pixel (Keshava, 2003). Spectral unmixing was chosen due to its ability to indicate fractions, abundances or proportion of each end member within a mixed pixels (Xin et al., 2006, Bateson et al., 2000). Linear unmixing involves two procedures, that is, end member spectra acquisition and proportion estimation (Quintano et al., 2012). The procedure models each spectrum as a combination of a finite number of spectrally distinct signatures (end members), whose coefficients range between 0 and 1 and adding up to 1 (Adams, 1986). This linear mixture model can be mathematically described for a pixel in band i, with the observed pixel reflectance R_i as a linear equation [1],

$$R_i = \sum_{i,j=1}^{n} f_j a_{ij} + \varepsilon_i \qquad [1]$$

Where:

f_j is the j^{th} fraction of end member in a pixel,

j is total number of end members in the scene,

a_{ij} is the pure reflectance from the j^{th} end members in the i^{th} pixel,

ε_i is an error term.

Only two end members from the image namely ‘burnt’ areas and ‘un-burnt’ areas were used. The end members were selected from the image after the image dimension had been reduced using the minimum noise fraction (MNF). The MNF transform is used to segregate and equalise the noise in the data, and reduce the computational requirements for subsequent processing (ENVI, 2006). After MNF, the bands containing ‘noise’ are not used in subsequent processing. Figure 2 below illustrates the concept for 2-dimensional plots used to locate end members. The end members (‘burnt’ and ‘un-burnt’ areas) are clearly separable, using band 1 and band 2 with little noise. Linear spectral unmixing was therefore subsequently used to find the abundances of ‘burnt’ and ‘un-burnt’ areas from the image pixels for the whole park. In cases where it was difficult to select many training samples for burnt areas, region growing techniques were used. In region growing, clusters of active fire pixels derived from the composite active-fire mask were used as seeds to iteratively “fill in” the surrounding burn scar. This enabled mapping of all the burnt areas.

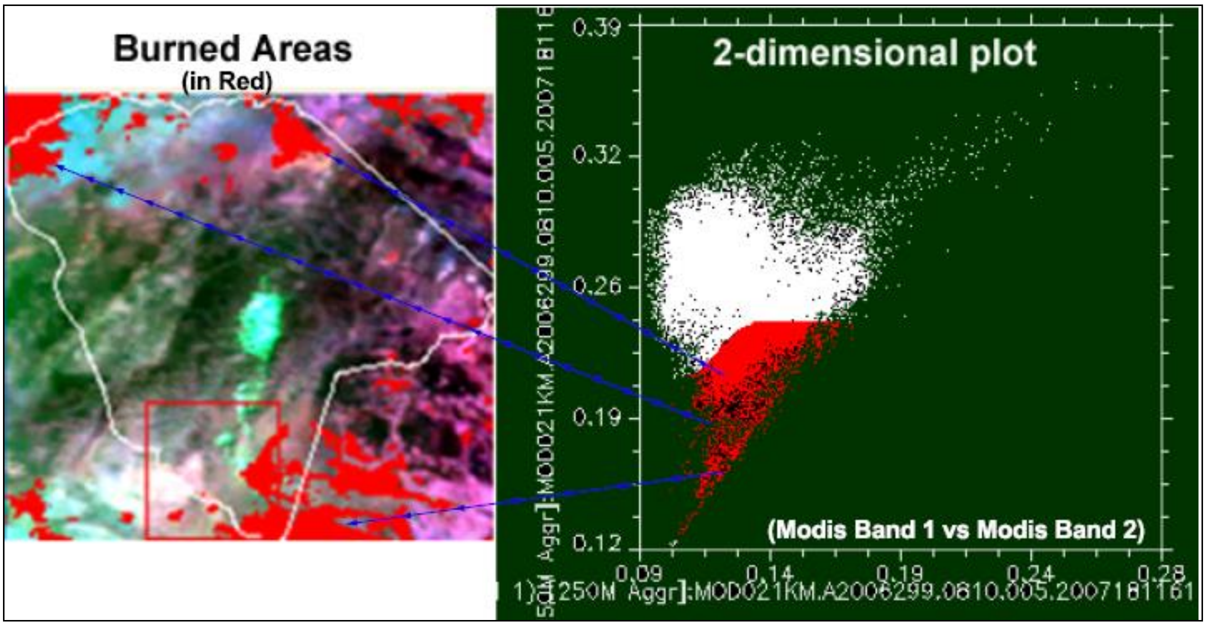

Figure 2: n-Dimensional visualiser used in selecting "pure" endmembers for image classification

3. Results and Discussion

Results illustrate that the relative cover of burnt patches could be separated with reasonable accuracy from the 'un-burnt' areas. Table 1 below summarises the total area classified as burnt areas for the years from 2000 to 2006. Overall, for all the years the areas classified as 'un-burnt' was significantly ($p<0.05$) higher than the burnt areas in Hwange National Park (Table 1).

Table 1: Total area classified as burnt area

Year	**Not burnt (km^2)**	**Burnt area (km^2)**	**Not burnt (%)**	**Burnt (%)**
2006	10689.74	4047.95	72.53	27.47
2005	10918.70	3818.98	74.09	25.91
2004	10092.05	4645.64	68.48	31.52
2003	12190.16	2547.56	82.71	17.29
2002	8995.76	5741.92	61.04	38.96
2001	12975.73	1761.95	88.04	11.96
2000	8458.90	5680.53	57.4 (+4.06% from clouds)	38.54

On a year by year basis, the years 2000 and 2002 experienced most fires and hence had the highest burnt areas (38.54% and 38.96% respectively) (Table 1 and Figure 3 & 4).

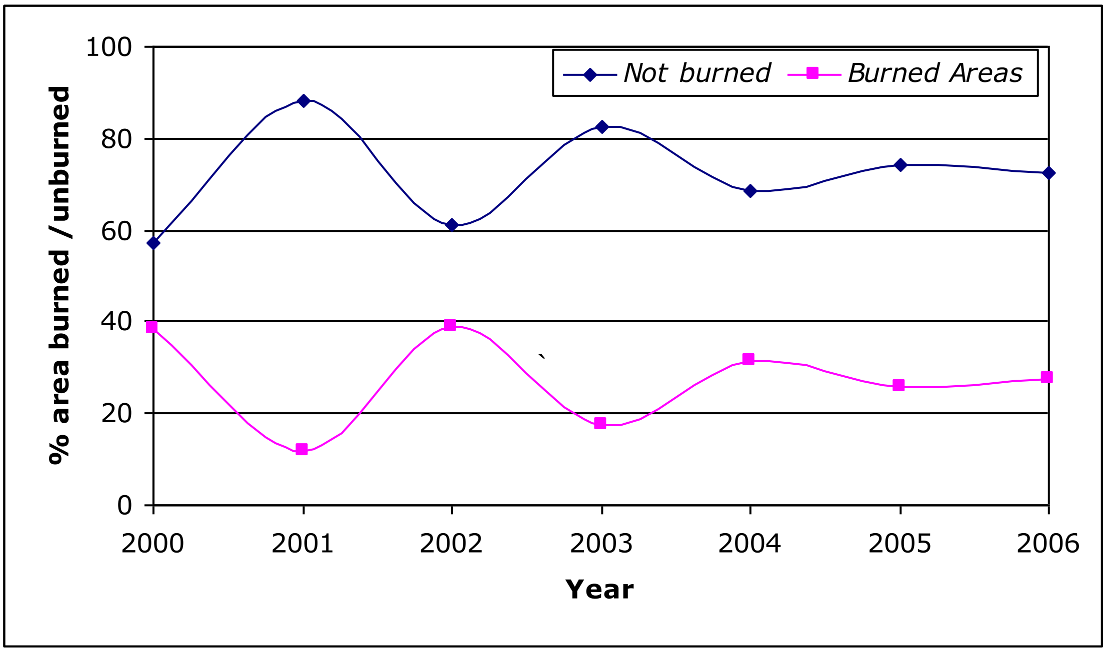

Figure 3: Trends in mapped burnt areas from 2000 to 2006

3.1. Fire frequency mapping

A fire frequency map was subsequently produced from the burnt area maps. Firstly the burnt area maps were converted into binary (presence or absence of fire) whereby fire presence was designated by one (1) and no fire by zero (0). These maps were therefore added in a GIS to obtain the fire frequency map (Figure 5) below.

The highest fire frequency (>4) in Hwange National Park was found to be at areas closest to the park boundary and especially so in the north, north-east and some central portions of the park. Table 2 below details the areas and percentage occupied by different fire frequencies. Areas with the highest fire frequency (7) occupy only 0.003 % of the park, with the largest area (31.44%) having experienced at least 2 fires within the 7 year period under study. Cumulatively, 86 % of the park had experienced at least a single fire within the 7 year period with 14% of the park not experiencing any fire at all. For management purposes, this implies that the probability of having a fire in the park is still very high, hence management of fire occurrence is critical both for the wildlife and the vegetation within the park. Additionally, special attention has to be paid to fire activities within the adjacent populated areas in the north and north east of the park since they experienced high frequency of fires.

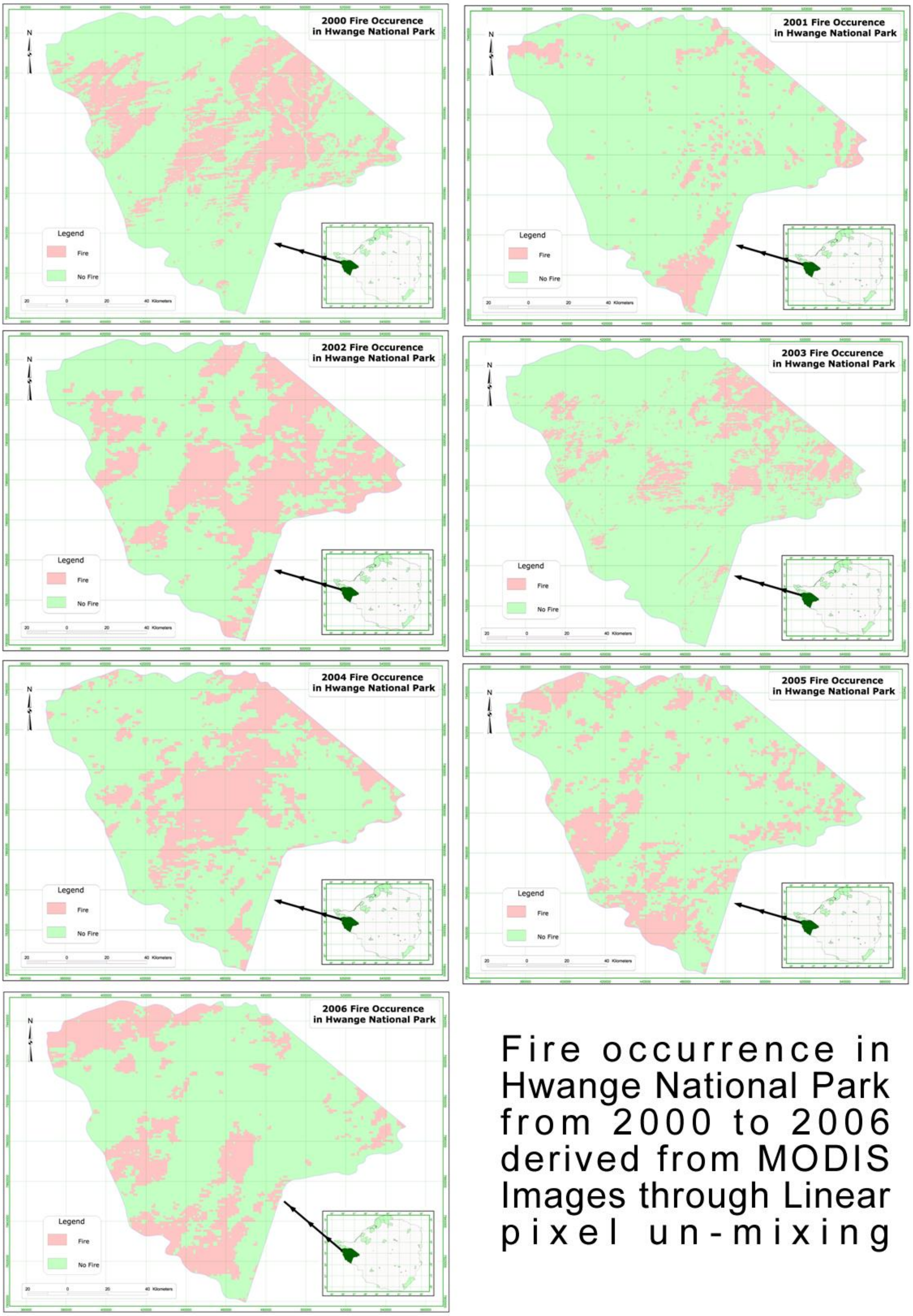

Figure 4: Fire occurrence from 2000 to 2006 derived from MODIS imagery

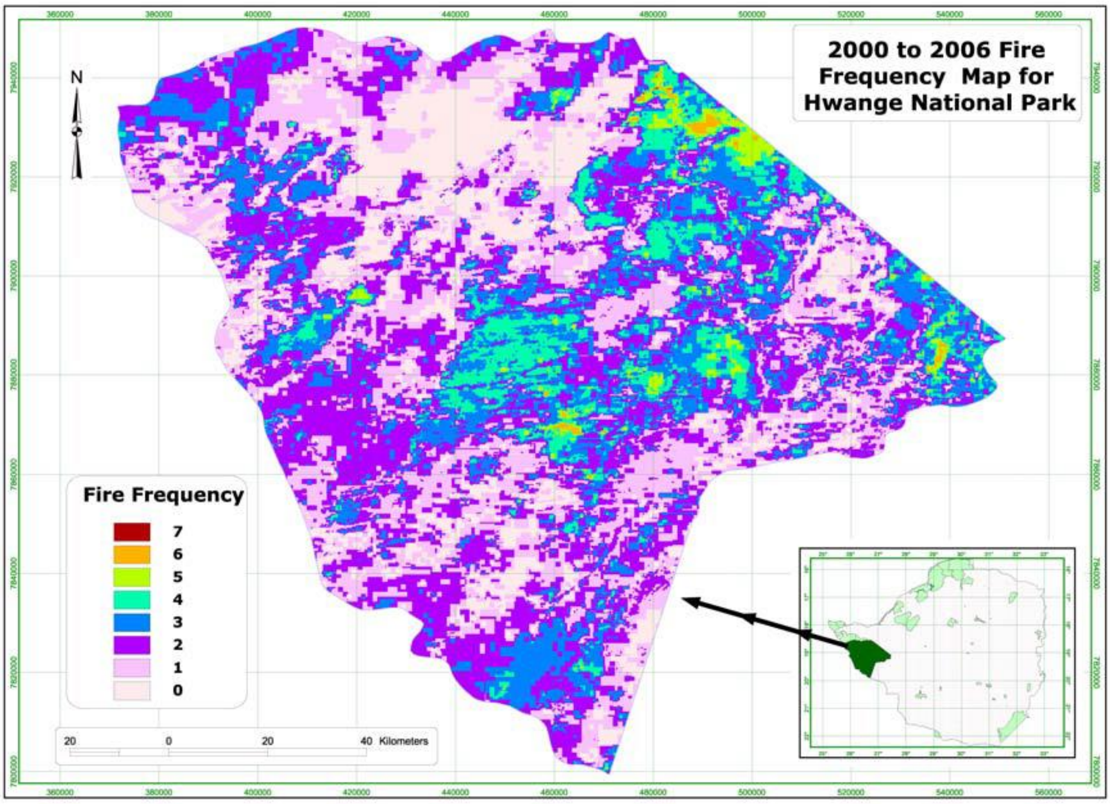

Figure 5: Fire frequency map for Hwange National Park from 2000 to 2006

Table 2: Areas occupied by different fire frequencies within Hwange National Park

Fire Frequency	Burnt area (km2)	Burnt area (%)	Cumulative Percentage
7	0.378	0.0026	0.0026
6	39.47	0.27	0.27
5	214.97	1.46	1.73
4	1050.63	7.14	8.87
3	2719.50	18.47	27.34
2	4628.73	31.44	58.79
1	4008.53	27.23	86.02
0	2058.54	13.98	100.00

3.2. Accuracy assessment

Validation of classification results involves statistical accuracy assessment of classified data, in order to measure the agreement of the classified image with the field observed data ("ground truth") using a classification error matrix (also called confusion matrix). Overall, accuracy was computed by dividing the total number of correctly classified pixels by the total number of reference pixels (Congalton and Green, 1999, Khorram et al., 2000). The classification error matrix was calculated using recorded data on observed fire occurrences available only from 2002 to 2006. Unfortunately data on observed fire occurrences for the years 2000 and 2001 was not available from the park records. For the period 2002 to 2006, the overall accuracy obtained ranged from 88% (2002); 90% (2003); 92% (2004); 96% (2005) and 98% in 2006. The observed differences on overall accuracy, despite using the same images and time of acquisition, could be attributable to possible inconsistencies in collecting fire occurrence data (“ground truthing”) by the park rangers. This fire information, used for accuracy assessment was collected by national park rangers during patrols but however, there was no noted systematic way of recording the fire occurrence information.

4. Conclusions

We have demonstrated the use of MODIS satellite imagery to map the occurrence of burnt areas from 2000 to 2006 in savannah ecosystems using linear pixel unmixing. A fire frequency map of Hwange National Park was produced showing areas likely to have repeated fires over several years. The advancement of geospatial technologies and capabilities, therefore, allow managers to make decisions based on the most current information available. Long-term and frequently updated fire maps are needed for land use, forestry, atmospheric chemistry, global climate, fire management studies and applications. The fire products are also important input for global change analysis as underlined by Malingreau and Gregoire, (1996) and Andreae, (1991). Among areas that could improve fire research are use of permanent satellites and finer spatial resolution (Malingreau and Gregoire, 1996, Hao and Liu, 1994) . The study is in agreement with an earlier study that utilised AVHRR in Levante, Spain, which is in the Mediterranean climatic region (Quintano et al., 2005) in focusing on regional and local fire products instead of global and continental focus as with most fire products. The study can go further and look at other aspects such fire risk analysis and effects of fire on different vegetation species within the park. Remote sensing and GIS have, therefore, demonstrated their importance in monitoring and management of fire hazards even in inaccessible regions as wildlife domiciled national parks.

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