THE EFFECT OF LAND USE PRACTICES ON THE SPATIAL AND TEMPORAL CHARACTERISTICS OF SAVANNA FIRES IN NAMIBIA

Der Effekt der Landnutzung auf die räumlichen und zeitlichen Merkmale der Savannenbrände in Namibia.

Der Naturwissenschaftlichen Fakultät
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zur
Erlangung des Doktorgrades Dr. rer. nat.

Vorgelegt von

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Summary

Namibia is often branded as the most arid country in sub-Saharan Africa. Despite this apparent aridity, a strong east-west rainfall gradient combined with typical sub-tropical seasonality in rainfall, produces fine biomass fuels which are sufficient in quantity and more than dry enough in quality to support widespread savanna fires every year.

These fires which have been burning in Africa for centuries are perceived by many as a scourge – something which should be suppressed at all cost. This outlook has been perpetuated by a succession of mostly foreign administrators and consultants, who are striving to enshrine their well-intended but somewhat misguided views in policy under the guise of integrated fire management.

Burned area mapping in Namibia dates back to the mid 1990’s when a NOAA AVHRR HRPT direct broadcast receiving station was installed at the Etosha Ecological Institute. While burned area data has been freely available, it only served to add fuel to the debate, because apparently large areas of Namibia’s woodlands burned “every year”. What was lacking is an analysis of the data that would provide answers to the questions of where does it burn? Where does it burn every year? At what time of year does it burn? And many others.

In order to answer these questions, the data needed to be re-processed. Not only to fill spatial and temporal gaps in the existing datasets, but also to produce burned area products that could be used to address the all-important issue of fire intensity/severity. This was not possible with the existing national datasets which had been aggregated to a single burned area map for a particular year. The AVHRR archive was therefore back-processed to produce monthly burned area maps of Namibia for the 10 year period from 1994 to 2003. In order to relate the fire season characteristics to the plant material that it relies on for fuel, a corresponding time series of NDVI images were processed to extract phyto phenological milestones. In order to reduce the data volume and to align it with existing biophysical datasets for Namibia, the burned area and NDVI products were aggregated by Quarter Degree Square (QDS). The milestone extraction from NDVI and temporal data extraction from burned area, was made possible by the development of two spreadsheet tools.
The data tables produced by the spreadsheet tools were combined and analysed in a GIS, to produce a series of maps that characterise Namibian fire regimes – temporally as well as spatially.

The results show that only 38% of the QDSs in Namibia were affected by fire during the 10 years covered by the study. Since the arid south-eastern parts of the country do not burn, the FAA is confined to the central and north-eastern areas. While a small proportion of this area starts burning within a month or two after the peak of the growing season, over much of the area the lag is between 4 and 6 months, giving rise to a peak in the burning season during the months of August and September. The burning season generally extends over a 2-6 month period, although some parts – notably in land use category (LUC-1) 1 agriculture and tourism on freehold land – the season is controlled and last for 1 month only. Over much of the FAA, the fire regime can be described as mild, with only 6% of the FAA subjected to a severe fire regime.

In order to evaluate the role of land-use on the fire regimes, Spearman’s rank correlation coefficients were calculated for fire return period, fire season duration, peak month for the fire season, and area burned (AB) paired with human population density, livestock density, landscape fragmentation, bush density, rainfall (RF), maximum NDVI value (Max NDVI), Mean NDVI value, NDVI greening up rate, peak month of NDVI, and sum of NDVI values (Total NDVI).

For the fire affected area as a whole, there are significant correlations between all of the variables, except for fire season peak and the NDVI variables. This confirms a degree of independence between the time of year when the most burning takes place, and the production of the biomass that is consumed. There is also no significant correlation between the NDVI green-up rate and the extent of burning. When considering the four spatio-temporal fire characteristics - Fire Return Period (FRP), Fire Season Duration (FSD), Fire Season Peak (FSP) and area burned, the strongest correlations are between:

- FRP and RF(-); FRP and Mean NDVI(-); FRP and Total NDVI(-), showing that an increase in rainfall (and therefore NDVI) is associated with more frequent burning.
- FSD and Bush Density(-); FSD and RF(+); FSD and Max NDVI(+); FSD and Mean NDVI(+), showing that an increase in rainfall (and therefore NDVI) is associated with
a lengthening of the fire season which is mitigated or inhibited by an increase in bush density.

- FSP and Human Population Density(-), showing that an increase in human population density is associated with an earlier peak to the burning season. Although this was the strongest relationship, it was still statistically weak while the remainder were very weak or not significant.

- AB% and Landscape Fragmentation(-); AB% and Livestock Density(-); AB% and Bush Density(-); AB% and Rainfall(+), showing that an increase of the area burned is associated with an increase in rainfall, but that this effect is reduced by landscape fragmentation, bush density and livestock grazing pressure.

There is a marked difference in the correlations between the spatio-temporal fire characteristics and the land use/environmental parameters within different land use categories. One category in particular, LUC-1 – agriculture and tourism on Freehold Land, differs radically from the rest. The reason for this is not so much a case of land use directly affecting the fire environment, but it provides the farmers with the ability to control fire events - an ability that stems from a highly developed road network, combined with a mobile community who perceives every fire as a threat and is prepared to come together to fight it at all costs.
Zusammenfassung

Namibia gilt als das trockenste Land im subsaharischen Afrika. Trotz der Aridität, einem starken Ost-West-Gradienten und der typischen subtropischen Saisonalität wird genügend Biomasse produziert, die auch trocken genug ist, um jährlich weit verbreitete Savannenbrände zu ermöglichen.

Feuer, die in Afrika seit Jahrhunderten betreffen, werden von Vielen als Plage angesehen, die es um jeden Preis zu unterdrücken gilt. Diese Ansicht wird durch meist fremde Administratoren und Berater fortgeführt. Sie bemühen sich, ihre gut gemeinten aber teilweise fraglichen Ansichten als integriertes Feuermanagement zu bewahren.


Um diese Fragen zu beantworten, mussten die Daten zuerst vorprozessiert werden. Dabei wurden nicht nur räumliche und zeitliche Lücken gefüllt, sondern auch Datenprodukte über Feuerflächen erstellt, die im Folgenden dazu dienten, sich der wichtigen Frage der Feuerintensität zu widmen. Dafür kam nicht nur der existierende nationale Datensatz zur Verwendung, aus dem für jedes Jahr eine Brandflächenkarte aggregiert wurde, sondern auch das AVHRR Archiv für eine 10-Jahresperiode, rückprozessiert für die Jahre 1994 bis 2003, um monatliche Brandflächenkarten für Namibia zu erstellen. Eine korrespondierende Zeitreihe des NDVI diente der Ermittlung der phänologischen Eckdaten, vor allem, um das zur Verfügung stehende Brennmaterial mit den Charakteristika der Feuersaison zu vergleichen. Zur Datenreduktion und um sie mit anderen biophysikalischen Datensätzen für Namibia in Deckung zu bringen, kam das Quarter Degree Square (QDS) Verfahren zum Einsatz. Die Extraktion der NDVI Eckdaten und der Zeitreihendaten für Feuerflächen wurde über die Entwicklung zweier Tabellenkalkulationen umgesetzt.
Die mit den Tabellenkalkulationen errechneten Datentabellen wurden in einem GIS kombiniert und zeitlich wie räumlich analysiert.


Die Rolle der Landnutzung in Bezug auf das Feuerregime wurde mit dem Rangkorrelationskoeffizienten nach Spearman abgeschätzt. Er wurde für die Feuerwiederkehrrate, die Dauer der Feuersaison, den Höhepunkt der Feuersaison und die Größe der Brandfläche in Bezug zur Bevölkerungsdichte, der Nutztierdichte, der Landschaftsfragmentierung, der Gehölzdichte, dem Niederschlag (RF), dem Maximum des NDVI (Max NDVI), dem mittleren NDVI (Mean NDVI), dem Beginn der NDVI-Vegetationsperiode und der Aufsummierung des NDVI (Total NDVI) berechnet.


Betrachtet man die vier raum-zeitlichen Feuercharakteristika – Feuerwiederkehrrate (FRP), Dauer der Feuersaison (FSD), Höhepunkt der Feuersaison (FSP) und Ausdehnung der Feuerflächen ergeben sich die stärksten Korrelationen mit:

- FRP und RF(-); FRP und Mean NDVI(-); FSD und Total NDVI(-), zeigen, dass ein höherer Niederschlag (und folglich höherer NDVI) mit einer höheren...
Feuerwiederkehrrate verbunden ist.

- FSD und Gehölzdichte(−); FSD und RF(+); FSD und Max NDVI(+); FSD und Mean NDVI(+), zeigen, dass ein höherer Niederschlag (und folglich höherer NDVI) mit einer Verlängerung der Feuersaison verbunden ist, aber durch eine höhere Gehölzdichte abgeschwächt oder verhindert wird.

- FSP und Bevölkerungsdichte(−), zeigt, dass eine höhere Bevölkerungsdichte mit einem früheren Höhepunkt der Feuersaison verbunden ist. Auch wenn dieser Zusammenhang der stärkste ist, ist er statistisch schwach, während der Zusammenhang mit anderen Variablen sehr schwach oder nicht signifikant ist.

- AB% und Landschaftsfragmentierung(−); AB% und Haustierdichte(−); AB% und Gehölzdichte(−); AB% und Niederschlag(+), zeigen, dass die Größe der von Bränden betroffenen Flächen mit der Niederschlagshöhe zunimmt, der Effekt aber von der Fragmentierung der Landschaft, der Gehölzdichte und dem Weidedruck abgeschwächt wird.

Acknowledgements

I would like to acknowledge the unwavering support that I received from my family during the course of this study. In particular, a special word of thanks to my wife Jan who always seemed to know when to encourage and when to rather say nothing.

Many other individuals and organisations played a role in some way. Those who are actually going to read this thesis will know who they are. I would like to thank all of them for their contributions.

Last but not least, I need to thank my supervisor, Prof. Dr. Cyrus Samimi for facilitating this study from inception to conclusion.

Johan le Roux
Windhoek
1 April 2011
Allgemeine Zeitung

„Feuer-Tsunami rollte heran“

Über 2000 Tiere nach Großbrand tot – 20.000 Hektar schwarze Erde


Von Dirk Heinrich


Windhoek • Das Feuer, das über die letzten Tage im Gebiet um Windhoek drohte, wurde endlich unter Kontrolle gebracht. Die Feuerwehr konnte das Feuer belassen, ohne dass die Umgebung betroffen war. Die Gäste der Stadt waren froh, dass die Stadt nicht in den Flammen lag.

Auf einem Feld bei Windhoek begann eine Dampferabbau vor der Stelle, wo das Feuer beginnen sollte. Die Bauern haben bereits einige Tage gebraucht, um sich auf die Situation einzustimmen. Der Großbrand hat zu einem jeden Bauern eine Schadensersatzbetrachtung gesetzt. Die Bauern haben bereits einige Tage gebraucht, um sich auf die Situation einzustimmen.

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I = Hrw

\( L_i = \alpha_i (D_i - D_{0i}) \)

\( \rho_i = 100 \times \frac{\pi L_i d^2}{E_{0i} \cos \theta} \)

\( \alpha_i = \frac{(L'_{0i} - L_{0i})}{(D_{0i} - D_{0i})} \)

\( \beta_i = L'_{0i} - \alpha_i D_{0i} \)

\( L_{\text{net}} = \alpha_i D_i - \beta_i \)

\( L_i^*(T_i) = \frac{\sum_{n=0}^{S_{\nu}} \beta(v_{1,n} T_i) \phi(v_{1,n})}{\sum_{n=0}^{S_{\nu}} \phi(v_{1,n})} \) for i = channels 3, 4 and 5.

\( \beta(v_{1,n}, T_i) = \frac{C_i (v_{1,n})^3}{(e^{(v_{1,n} T_i)} - 1)} \) in Wm\(^2\)sr\(^{-1}\)cm

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\[ v_{i,n} = v_{1,i} + n\delta v_i \] \hspace{1cm} \text{in cm}^{-1} \hspace{1cm} \text{Equation 4-8 \ldots\ldots. 38}

\[ NDVI = \frac{(NIR - R)}{(NIR + R)} \] \hspace{1cm} \text{Equation 4-9 \ldots\ldots. 40}

\[ r = \frac{\sum xy}{\sqrt{\left(\sum x^2 \sum y^2\right)}} \] \hspace{1cm} \text{Equation 7-1 \ldots\ldots. 100}

\[ r = \frac{\sum XY - \frac{\sum X \sum Y}{n}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{n}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{n}\right)}} \] \hspace{1cm} \text{Equation 7-2 \ldots\ldots. 100}

\[ r_{ij} = \frac{\sum_{i=1}^{n} (\text{rank of } x_i)(\text{rank of } y_i) - \frac{n(n+1)^2}{4}}{\sqrt{\sum_{i=1}^{n} (\text{rank of } x_i) - \frac{n(n+1)^2}{4}} \sqrt{\sum_{i=1}^{n} (\text{rank of } y_i) - \frac{n(n+1)^2}{4}}} \] \hspace{1cm} \text{Equation 7-3 \ldots\ldots. 101}

\[ r_s = 1 - \frac{6\sum d_i^2}{n^3 - n} \] \hspace{1cm} \text{Equation 7-4 \ldots\ldots. 101}
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<td>AB%</td>
<td>Area Burned (percentage)</td>
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<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>bit</td>
<td>Binary digit. The basic unit of information in computing</td>
</tr>
<tr>
<td>BT</td>
<td>Brightness Temperature</td>
</tr>
<tr>
<td>BURS</td>
<td>Bradford University Remote Sensing</td>
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<tr>
<td>CART</td>
<td>Classification and Regression Trees</td>
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<tr>
<td>CD</td>
<td>Compact Disk</td>
</tr>
<tr>
<td>CDA</td>
<td>Command and Data Acquisition</td>
</tr>
<tr>
<td>DN</td>
<td>Digital Number</td>
</tr>
<tr>
<td>DoF</td>
<td>Directorate of Forestry</td>
</tr>
<tr>
<td>DOS</td>
<td>Disk Operating System</td>
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<tr>
<td>ER</td>
<td>Earth Resource (Mapper)</td>
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<tr>
<td>FAA</td>
<td>Fire Affected Area</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>FRP</td>
<td>Fire Return Period</td>
</tr>
<tr>
<td>FSD</td>
<td>Fire Season Duration</td>
</tr>
<tr>
<td>FSP</td>
<td>Fire Season Peak</td>
</tr>
<tr>
<td>GAC</td>
<td>Global Area Coverage</td>
</tr>
<tr>
<td>GCP</td>
<td>Ground Control Point</td>
</tr>
<tr>
<td>GIMMS</td>
<td>Global Inventory Modelling and Mapping Studies</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GLCF</td>
<td>Global Land Cover Facility</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Centre</td>
</tr>
<tr>
<td>HRPT</td>
<td>High Resolution Picture Transmission</td>
</tr>
<tr>
<td>IDRISI</td>
<td>Not an acronym. Image processing software named after a medieval cartographer and geographer.</td>
</tr>
<tr>
<td>IFOV</td>
<td>Instantaneous Field Of View</td>
</tr>
<tr>
<td>IRDNC</td>
<td>Integrated Rural Development and Nature Conservation</td>
</tr>
<tr>
<td>KNP</td>
<td>Kruger National Park</td>
</tr>
<tr>
<td>LAC</td>
<td>Local Area Coverage</td>
</tr>
<tr>
<td>LARST</td>
<td>Local Application of Remote Sensing Technology</td>
</tr>
<tr>
<td>LUC</td>
<td>Land Use Category</td>
</tr>
<tr>
<td>MAUP</td>
<td>Modifiable Areal Unit Problem</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>MMU</td>
<td>Minimum Mapping Unit</td>
</tr>
<tr>
<td>MO</td>
<td>Magneto-optical</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>MS</td>
<td>Microsoft</td>
</tr>
<tr>
<td>MVC</td>
<td>Maximum Value Composite</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
</tr>
<tr>
<td>NESDIS</td>
<td>National Environmental Satellite, Data, and Information Service</td>
</tr>
<tr>
<td>NFFP</td>
<td>Namibia Finland Forestry Programme</td>
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<tr>
<td>NIR</td>
<td>Near-infrared</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>NOM</td>
<td>NOAA Operations Manager</td>
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<tr>
<td>NRI</td>
<td>Natural Resources Institute</td>
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<tr>
<td>ODA</td>
<td>Overseas Development Agency</td>
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<tr>
<td>PAR</td>
<td>Photosynthetically Active Radiation</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>POD</td>
<td>Polar Orbiter Data</td>
</tr>
<tr>
<td>QDGC</td>
<td>Quarter Degree Grid Cell</td>
</tr>
<tr>
<td>QDS</td>
<td>Quarter Degree Square</td>
</tr>
<tr>
<td>rho</td>
<td>17th letter of the Greek alphabet. Denotes Spearman's rank correlation</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SPOT</td>
<td>Satellites Pour le Observation de la Terre or Earth-observing Satellites</td>
</tr>
<tr>
<td>TM</td>
<td>Thematic Mapper (Landsat)</td>
</tr>
<tr>
<td>USDA</td>
<td>U.S. Department of Agriculture</td>
</tr>
</tbody>
</table>
“Don’t try and kid me man-cub and don’t get in a stew
What I desire is man’s red fire so I can be like you”
The Jungle Book soundtrack

INTRODUCTION

Fire – the scale of the issue.
Control over fire is one of the traits that set man apart from animals. Perhaps more than any other event that has shaped human prehistory, the ability to use fire has allowed us to exert our dominance over the landscape and the creatures that share it with us. Several million years later, anthropogenic fire continues to shape the environment to the point where it is referred to by some as the most widespread ecological disturbance in the world (Trollope, 1984). The simple inclusion of the word “disturbance” adds a negative connotation to fire events. That fire has the potential to be one of the most destructive forces on earth cannot be denied. Every year lives are lost, property destroyed and habitats altered by uncontrollable wildfires. The fact remains however, that fire in itself is neither good nor bad. Its dire consequences come from our continued inability to control something that we supposedly grasped control over all those millennia ago. Now, as was the case then, we are still only masters of ignition. Starting the combustion process is easy enough. Retaining control however, has not only remained a challenge, but has become absolutely essential in a world with a growing human population and a shrinking natural resource base.

The impact that this rapidly expanding population has on the planet, has over the last few decades found a focus in the area of climate change and the emission of so-called greenhouse gases into the earth’s atmosphere. Industrialised nations and their burning of fossil fuels were immediately obvious sources, but attention soon turned to less developed countries and the burning of biomass (Crutzen et al 1979). Since then, many studies have investigated fire at the global scale. Early work focused on the physics involved in the detection of fire events using data from a variety of satellite sensors (e.g. Matson and Stephens 1987, Robinson 1991, Chuvieco and Pilar 1994). This was soon followed by work that described the spatial and temporal characteristics of active fires around the world (e.g. Dwyer et al 1998). With the launch of satellites that carried sensors dedicated to fire observation, scientists embarked on attempts to develop global algorithms for the detection of active fires (e.g. Arino and Plummer
2001) and burned area (e.g. Roy et al 2002). The main focus of studies at the global scale however, remains the calculation of emissions from biomass burning (e.g. Crutzen and Andreae 1990).

These global studies located the main source of biomass burning emissions in the tropics, accounting for more than 70% of the fires detected in a 12 month period between April 1992 and March 1993 (Dwyer et al 1998). Furthermore, the African continent was responsible for over 50% of all fires detected in that study. With the shift in focus from the global level to a continental scale, one would expect a corresponding change in the research focus. A few studies did investigate other parameters such as the seasonal distribution of savanna fires (e.g. Cahoon et al 1992) as well as interannual variations in African fires (e.g. Koffi et al 1996), but at continental scales, the main preoccupation of the research community remains the calculation of greenhouse gas emissions (e.g. Barbosa et al 1999, Scholes and Andreae 2000).

The savanna biome is the most fire prone vegetation type in the world (Dwyer et al 1998). Although the bulk of African savanna areas are located north of the equator, a significant portion of it is located in the Southern African subregion. Investigating fire events at this scale, the emphasis can finally shift away from calculating total emissions from biomass burning. Researchers are now able to focus on the effects of fire on vegetation, and not surprisingly, localised ecological studies now dominate. These range from long term investigations into the impact of different fire regimes on the vegetation of the Kruger National Park in South Africa (Biggs et al 2003), to the active use of fire to control bush encroachment (e.g. Trollope 1980, Sweet 1982). Some studies have shown the effect of fire regimes on certain tree species (e.g. Danthu et al 2002, Kennedy and Potgieter 2003), while others have investigated the determinants of fire intensity in savanna vegetation (e.g. Govender et al 2006).

The local effects of fire, focusing on villages, families or individuals, are apparently well known. We all seem to know that at this level, fire is applied by farmers as a method of land preparation, by pastoralists to rejuvenate the grazing for their livestock, by hunters and gatherers to improve visibility, etc. The effects are equally clear to see: bush turns to field, dry grass sprouts green, tall almost impenetrable grassland turns into open
accessible plain. Nevertheless, studies have been carried out to investigate people’s attitudes towards the use of fire (e.g. Mbow et al 2000).

From the above, it seems that there is a clear hierarchical order at which fire issues are being researched, not only in terms of geographical scale, but also in terms of the number of studies that are conducted and the relative importance of the perceived impact of fire at any particular level. This hierarchy is shown graphically in the figure below. Our current knowledge on fire issues is also reflected in this order. Much has been learned about what was previously unknown - biomass burning's contribution to the global climate change/greenhouse gas issue. We also know much more now, about which countries and which biomes are responsible for most of these pyrogenic emissions, and we think we know why individuals are setting fires and how fires are affecting them.

The part that seems to be missing is the area that doesn't quite fit into this scheme. The results of global/continental studies are too coarse to be applicable at the national level. Biome-wide studies ignore parts of a country which fall outside the biome under consideration, and local studies are too specific to be applicable across the rest of the country. An attempt at synthesising the fire situation in the world's most fire prone continent highlighted this gap in our knowledge: the International Forest Fire News –
Africa Fire Special (Goldammer (ed), 2000) contains reports from only 10 countries. Literature searches turn up almost no publications that characterise fire regimes at the national level for any African country. The reason for this is twofold:

1. Within the international community, there is insufficient reason to focus their expertise and resources within the arbitrarily drawn boundaries of any particular African country. Remote Sensing offers the ability to generate data for entire regions all at once. Why go to the trouble of producing fire statistics for several countries, and then adding it all up to generate figures for the region of interest?

2. Within most African countries, there is insufficient expertise and or resources to conduct these studies. In many countries, addressing fire issues both at the academic and management levels, are being hampered by unstable political conditions, military conflict, as well as a lack of public and or government commitment (Goldammer (ed), 2000).

Fire information at the national level is of importance for a number of reasons. In Namibia, the adverse effects of frequent and uncontrolled fires threaten people's livelihoods by causing damage to property and infrastructure, reducing the productive capacity of the land, destroying resources such as grazing and thatch grass as well as other non-timber forest products (DoF/NFFP 2004). This in turn has an impact on the national economy. This economic impact can be illustrated by examining the effect of grazing loss through uncontrolled fires. Communities in the northern communal areas mostly rely on subsistence farming. Regular crop failures brought on by failed rains or flooding often require government intervention in the form of food aid. Add livestock losses due to burnt grazing to these woes, and the economic burden on the government escalates dramatically. In the freehold farming areas, grazing needs to be leased from neighbours if more than about 75% of the farm's grazing is destroyed by fire (P. Gouws 2001, pers. comm.). During the 2001 fire season, 781 farms were affected by fires (Le Roux 2001). If half of the affected farmers were forced to lease grazing land, the cost would amount to about N$12 million. Clearly, an understanding of Namibia's fire regimes would be a prerequisite for the formulation of policy. Similarly, continuous monitoring would be required to evaluate the efficacy of policies that are implemented. This study therefore aims to provide these two tools to strategic decision makers.
Objectives and Research Goals

**Objective 1:** To characterise Namibian fire regimes in the spatial and temporal domains.

Goals:

- Production of a dataset consisting of digital burned area maps for Namibia, aggregated to a monthly level and spanning a ten year period from 1994 to 2003.
- Development of a semi-automated system to extract a range of relevant metrics from this dataset.
- Production of comparable vegetation index datasets.
- Development of a semi-automated system to extract a range of relevant metrics from this dataset.
- Combining these metrics to produce spatially explicit datasets that characterize Namibian fire regimes.

*Research question:* Is it possible to develop semi-automated systems that enable the characterisation of Namibian fire regimes?

**Objective 2:** To explore the effect of different land use practices on the spatio-temporal parameters obtained from objective 1.

Goal:

- Test the strength of the relationships between various land use parameters and relevant fire regime characteristics.

*Research question:* Which land use parameters are the main drivers of change in Namibian fire regimes?

Intermediate steps required

- Digital processing of satellite image data to produce burned area and vegetation index datasets.
- Development of the spreadsheet tools.
- Post-processing of the datasets in a GIS to produce data tables.

**Thesis structure**

Chapter 1 introduces the study area – Namibia – and provides background information that is required for an understanding of the fire regimes.

Chapter 2 deals with the issue of fire in Namibia, and discusses the need for fire data.

Chapter 3 introduces the mapping units used throughout this study, and discusses its relevance to the Namibian situation.

Chapter 4 describes the satellite image data and the fire and vegetation datasets that were derived from it.

Chapter 5 discusses the different fire regimes in Namibia.

Chapter 6 introduces the different land use categories and their associated parameters.

Chapter 7 explores the relationships between land use parameters and fire regimes.

Chapter 8 provides a summary of the findings, and an outlook for future research.

**NOTE**

This study used Remote Sensing and GIS techniques to analyse spatially explicit environmental phenomena over time. Extensive use is made of illustrations in the form of maps and images throughout this thesis, to provide a clearer understanding of the geospatial relationships that are referred to in the text.
“Contrasting beautiful Namibia,
Namibia our country.
Beloved land of savannas,
Hold high the banner of liberty”

From the Namibian National Anthem

1 NAMIBIA – THE COUNTRY AND ITS PEOPLE

1.1 Physical Geography

Namibia is a large country on the south-western coast of Africa. It is bordered by Angola and Zambia in the north, Botswana in the east, South Africa in the south and the Atlantic Ocean in the west. Covering an area of about 823 678 square kilometres, it is roughly the same size as Germany and France combined. The country has two distinct geographic regions: a relatively narrow flat coastal plane, and a large interior highland covered by shallow soils in the west and deep sand in the east. These two regions are separated by a narrow escarpment zone characterised by rugged mountains. As a transition zone, the escarpment plays an important ecological role, and provides habitats for much of Namibia's endemic fauna.

The coastal plain forms part of the Namib Desert, which runs down the entire 1500 kilometre length of Namibia's coastline. In the north and south, the Namib is a mixture of barren gravel plains with or without sand dunes (figure 1.1.1), while the central part is covered by a sand sea of very large dunes which do not support vegetation (figure 1.1.2).

Figure 1.1.1 Northern and Southern Namib: Shifting sand dunes on gravel plains, with escarpment mountains in the distance.

Figure 1.1.2 Central Namib: Very large sand dunes reaching down to the sea.
In the north and south of the country, at a distance of about 100 to 150 kilometres from the coast, the escarpment zone rises steeply towards the interior plateau. This area is characterised by rugged mountains with very little vegetation cover.

The valleys may consist of equally barren gravel plains (figure 1.1.3), or may have sparse grass cover on sandy soils (figure 1.1.4). The central part of the escarpment zone has been weathered away, and here the gravel plains stretch inland from the coast for several hundred kilometres. Namibia’s highest mountain, the Brandberg, rises dramatically from this plain to a height of 2579 metres above sea level.

Beyond the coastal plain and escarpment zone, the greater part of the Namibian interior lies at an altitude of between 1000 and 1400 metres above sea level. In the centre of the country, the Khomas Hochland lies at an even higher elevation of between 1700 and 2000 metres above sea level, giving Windhoek a relatively mild year round climate. Namibia has no perennial rivers of its own, although some of Africa’s greatest rivers flow along its borders (figure 1.1.5). The Kunene River rises in the highlands of Angola and forms the north-western border of Namibia. The Okavango River has its origin in the same area, and forms the central-eastern border of Namibia before crossing the Caprivi strip on its way to the Okavango delta in Botswana. The Kwando-Linyanti-Chobe river system forms the southern border of the Caprivi region, while the Zambezi River forms its northern border. In the south, the Orange River forms the border between Namibia and South Africa. The country does have many ephemeral rivers, most of which “flow” westwards from the central plateau towards the Atlantic Ocean.
1.2 Climate

Namibia is often labelled as the driest country in sub-Saharan Africa (Seely and Jacobson 1994, Ashley 1996). It is therefore not surprising that rainfall, or the absence of it, is a dominant feature of Namibian life. Only 8% of the country can be classified as sub-humid, while 37% is semi-arid, 33% is arid and 22% is desert (de Klerk, 2004). This aridity is caused by the country’s geographical position: straddling the Tropic of Capricorn on the west coast of Africa (figure 1.2.1), Namibia is situated in an area that is affected by subtropical high pressure cells, as well as the Inter-tropical Convergence Zone (Nieuwolt, 1977).
For most of the year, the Subtropical High Pressure Zone hangs over the country, feeding in dry air from the interior of the subcontinent or from the Atlantic Ocean. During the summer months of September to April however, the weather systems move southward, allowing the tail end of the Intertropical Convergence Zone to reach parts of Namibia from time to time, feeding in moisture laden air and causing sporadic convective thunderstorms.

This phenomenon gives rise to a steep rainfall gradient across the country, with annual precipitation figures ranging from about 650 mm in the north-east, to 25 mm or less in the south-west (figure 1.2.2). There is much variation in rainfall between seasons as well as within any given season. This variability increases with decreasing rainfall (Engert, 1997). As a result, the reliability of the rains is higher in the north-east and lower in the south-west (figure 1.2.3).
The highest daytime temperatures are recorded during the summer months of September to February, with temperatures often exceeding 30° Celsius (figure 1.2.4). Relatively low temperatures are experienced across the country from May to early September, while sub-zero temperatures may be recorded during the winter months of July and August (figure 1.2.5).

1.3 Vegetation

The most recent Namibian vegetation map was produced in 2000-2001 as part of the Atlas of Namibia project, when a team of botanists/plant ecologists synthesized work done since the first comprehensive vegetation map was produced by Professor Adolf Engler in the early 1900’s. According to this synthesis, Namibia has 29 discrete vegetation types which can be grouped into 5 biomes (figure 1.3.1).

Biomes are major regional ecological communities that usually correspond to plant ecologist’s classification of plant formations (Smith, 1980). In other words, they are large areas that share loose associations of vegetation. Of the 5 biomes which occur in Namibia, the Tree-and-shrub Savanna biome is by far the largest, covering more than 50% of the country. This biome can be divided into 2 sub-biomes: Broadleaved Tree-and-shrub Savanna in the north-east of the country, and Acacia Tree-and-shrub Savanna in the central eastern and central northern parts.
Figure 1.3.1 Vegetation types, Biomes and sub-Biomes of Namibia. (Adapted from Mendelsohn et al, 2002)
Since plant life is often determined or at least influenced by climate features and soil properties, these characteristics are sometimes associated with a particular biome. In Namibia, the broadleaved savanna is characterized by tall trees from several genera that are able to form large expanses of reasonably dense woodland in areas where conditions are favourable (figure 1.3.2).

The herbaceous layer is apparently continuous and consists of tall grass species that tend to lose their palatability when they dry out. Mean minimum and maximum temperatures do not differ greatly from the Acacia sub-biome, but rainfall is higher and less variable than in other parts of the country. High rainfall tends to leach nutrients from the soil, and much of this sub-biome is covered by deep Kalahari sands which are generally low in nutrients, particularly phosphorous (Mendelsohn and el Obeid, 2005).

Acacia savanna, as the name suggests, is dominated by trees from a single genus, *Acacia*, dotted across large areas of grassland (figure 1.3.3). Many parts of this sub-biome are affected by so-called bush encroachment, with an associated decrease in herbaceous cover. Even in unaffected areas, the grass cover tends to be lower and sparser than in the Broadleaved savanna. Soils here are generally much shallower and often contain a high proportion of gravel, but due to the lower rainfall, contain more nutrients and supports grass species that remain palatable when dry.

Rainfall, or more exactly soil moisture balance, is the overwhelming factor that determines the spatial distribution of savanna grassland in southern Africa (Tinley,
In Namibia, two other factors act as equally important determinants in both the Acacia and Broadleaved savanna biomes - fire and grazing pressure (Mendelsohn et al, 2002). Both of these are inextricably linked to people.

1.4 People

Namibia is one of the most sparsely populated countries on earth. The relatively large size of the country, coupled with a small population of around 2 million people, means that there are only about 2.5 Namibians per km². Such an even distribution of people is of course not the case, and the population is in fact highly clustered, with densities per km² ranging from 0 in uninhabitable areas such as the Namib Desert, to more than 100 in some urban and north-central areas (figure 1.4.1). In 1996 it was estimated that about 25% of the population lived on just 1% of the land - in the Cuvelai drainage area of north-central Namibia (Ashley, 1996).

![Population density distribution. Large parts of the country, such as the Namib Desert along the coast, are uninhabitable. (Adapted from Mendelsohn et al, 2002)](image)

Namibia has a cultural heritage that is as contrasting and diverse as its landscapes. There are no fewer than 25 different languages or major dialects spoken across the country, not including other languages of European origin such as English, Afrikaans and German (Mendelsohn et al, 2002). These 25 languages or major dialects can be grouped into 6 families: Oshiwambo, Caprivian, San, Khoekhoe, Kavango and Herero. The greatest diversity is to be found in the northern parts of Namibia, particularly in the north-central region, where the Oshiwambo family of languages is comprised of 9 different dialects.
Almost 80% of Namibia's surface area is covered by rural areas that consist mainly of sparsely populated freehold farming areas, and sparsely or densely populated communal farming areas. The remaining 20% is mostly national parks/wildlife reserves. Farming is clearly the major occupation in Namibia, with livestock husbandry predominating over crop production. This direct reliance on the land, coupled with a population that is growing faster than any non-agricultural industry, continues to put more and more pressure on the country's natural resource base.

1.5 Summary

Namibia is a large country with a small human population, situated on the southwest coast of Africa. The majority of Namibians live on communally owned land, where they rely on primary production and natural resources for their livelihood. The climate is arid to extremely arid over much of the country, with unreliable rainfall in the form of heavy tropical thunderstorms occurring during the summer months of November to April. Winter temperatures can drop to below 0° Celsius in some parts of the country, while summer temperatures in excess of 40° Celsius are not uncommon.

These climatic conditions have prevailed for millions of years, and have given rise to not only one of the oldest deserts in the world, but also one of the most widespread and fire prone vegetation types on earth – the savanna. Strongly seasonal rainfall patterns cause annual cycles of herbaceous biomass production followed by a long dry season that cures these grasses into combustible fuels, while a small but highly clustered human population provides the ignition source and space for fires to flourish.
"Fire and People do in this agree,  
They both good servants, both ill masters be."
Fulke Greville - Inquisition Upon Fame and Honour (1633)

2 FIRE IN NAMIBIA – A BURNING ISSUE

2.1 Introduction

Three elements need to come together in sufficient quantities in order for combustion to take place: heat, oxygen and fuel (figure 2.1.1). Of all the known planets in the universe, Earth is the only one where these requirements are met. Others, such as Jupiter, may have lightning storms that generate enough heat to ignite a fire, but fuel and oxygen is either insufficient or absent. Isolated wildfires that actually consumed vegetation have been part of the Earth’s suite of natural phenomena since the Late Devonian, some 450 million years ago (Cressler 2001), while widespread biomass burning is evident from the Early Carboniferous, about 350 million years ago (Scott 2000). By contrast, man’s association with fire is rather more recent, with the earliest direct evidence of its use by hominids dating back no more than 1.5 million years, to a campfire in the Swartkrans cave in South Africa (Brain and Sillent 1988).

Anthropogenic biomass burning is more recent still, and for sub-Saharan Africa dates back a mere 400 000 years, as evidenced by a dramatic rise in elemental carbon abundance from that period. The uniqueness of this peak within the last million years seems to indicate that it is due to man’s active application of fire to the landscape, and it can therefore be concluded that we have had significant control over fire regimes.

![Figure 2.1.1 The three essential elements of fire: Oxygen, fuel and heat. Reduction or removal of any one element will reduce or extinguish the fire.](image-url)
since the start of the Holocene (Bird and Cali 1998). Man-made fires continue to flourish where it all started thousands of years ago. On a global scale, and regardless of the season, Africa stands out as a fire continent (figure 2.1.2).

Based on the analysis of SPOT Vegetation data, it is estimated that for the period from January to December 2000, the total area affected by fire globally amounted to about 3.5 million km² (Tansey et al 2004). A calendar year might not be the optimal time frame with which to capture a full fire season, but it is appropriate for most southern tropical regions where the majority of fires occur during the winter dry season between June and October. Even so, Africa dominates the global burned area, and accounts for more burned area per year than all other continents combined (figure 2.1.3).
Despite the antiquity of biomass burning and its widespread use by man around the world, many misconceptions about the ecological role of fire remain. More often than not it is villainised and held up as a destructive force that should be suppressed at all cost, and eventually prevented from ever occurring again. There is no denying that “fires threaten human lives, property and natural resources in Southern African savannas” (Siljander 2009). At the same time, there is overwhelming evidence that anthropogenic fire is not only an integral part of savanna ecology, but also an essential savanna maintenance mechanism (Bird et al 2008, Govender et al 2006, de Klerk 2004, Bond and Midgley 2003, Roques et al 2001, Russell-Smith et al 1997, Trollope 1984, Huntley 1982, Tainton 1981).

What is required then, is a paradigm shift from attempts at fire suppression, to truly integrated fire management - a moving away from controlling whether it is going to burn this year, to controlling what is going to burn, and when during the year will this happen. These two factors play a vital role in determining the crucial element of biomass burning - how will it burn. Will the fire be hot and devastating or cool and rejuvenating? Will it burn vast areas and jump across the widest of fire breaks (figure 2.1.4), endangering people and property and consuming large trees in its path, or will it burn a patchwork mosaic and stop at the edges of seemingly insignificant cattle paths or game trails (figure 2.1.5), having recycled dead herbaceous material into soil nutrients?
2.2 Fire policy and fire information

Policy is a precursor to the law, and information is the precursor to policy. Without a thorough understanding of the situation, policy decisions are likely to remain out of step with practice, and therefore doomed to failure. Fire policy first appeared in Namibia under the rule of the Deutsche Kolonialgesellschaft für Südwestafrika who banned all fires in 1888, because “deliberate burning destroyed forests and other vegetation” (Goldammer, 1999). This misinformed sentiment remains entrenched in current thinking, as illustrated by the emphasis on suppression in this extract from Namibia’s National Forest and Veld Fire Management Policy – 1st draft (DoF-NFFP, 2004):

3. Proposed Statements on Policy Means
3.1 Forest fire management, including prevention and suppression

- Forest and veld fire prevention, pre-suppression, suppression and post-fire rehabilitation will be promoted as integral parts of the protection and sustainable management of all land resources to produce timber, non-timber forest and veld products as well as environmental services.
- Integrated forest and veld fire management, whereby all aspects of prevention and suppression are considered together, will be promoted as the main approach to fire management, while recognising that the approaches must be adapted depending on the role of fire in various ecological zones and the prevailing socio-economic conditions.
- Scarce government resources will be allocated to priority areas based on the extent of the fire problem, and values at risk, including human lives, damage to property, biodiversity and other conservation values. Priority areas include at least Caprivi, Kavango, Omusati, Otjozondjupa, Oshana, Omaheke, and Khomas (regions).
The proposed statements continue with eight further bullet points, all of which focus on fire prevention and or suppression. There is no proposed statement on prescribed burning.

This pre-occupation with fire as an unnecessary evil that needs to be eradicated is not unique to Namibia. It has been prevalent not only across Africa, but with more or less justification, in most countries around the world (figure 2.2.1). In the words of Bernard Fernow, the third chief of the USDA's Division of Forestry of the United States from 1886 – 1898, 

"...the whole fire question in the United States is one of bad habits and loose morals. There is no other reason or necessity for these frequent and recurring conflagrations." (in Langston, 1996). More than a century later, in his closing speech at the 24th FAO regional conference for Africa, the Malian Prime Minister summarised what the delegate’s views on fire were: “With regard to the age-old practise of bush fires, you have wisely called for the building of national and producer capacity to prevent, control and manage this scourge” (FAO, 2006).

How African Administrators came to view an age old land management tool as a scourge has been the topic of investigation by a number of authors in recent years. Laris and Wardell (2006) argue that at least for the West African situation, this attitude was entrenched since the mid nineteen hundreds by European scientists who firmly believed that the widespread annual burning that they found in their new colonies would result in degradation of valuable forests into more open and (to them) less valuable savannas. Across the border from Namibia, the Zambian situation was reviewed by Eriksen (2007), who is of the opinion that the controversy over traditional burning practices as an integral part of indigenous land management was due to a mismatch between contemporary fire policies prescribed by officialdom, and ancient fire practices prescribed by common sense.

There is no forest fire policy for Namibia, although the Directorate of Forestry is currently in the process of developing one. The first draft was produced in 2004 by the
Namibia-Finland Forestry Programme (DoF-NFFP, 2004). Not surprisingly, given the well-intentioned but Eurocentric background of the drafters, the policy does not embrace the importance of seasonal burning in the local land management calendar. Instead, it focuses on fire suppression at the expense of truly integrated fire management. The development of this draft document was based in part on a “review of documents and implications for fire policy information” (DoF-NFFP, 2002). The reviewer’s clearly one-sided approach to the issue is summarised in a section which he calls “The Fire Problem”, where he lists the negative effects of fires. These include diminished forest resources, biodiversity and a degraded environment. There are no specific references to articles/publications/reports to back up these rather sweeping statements, although the document contains a bibliography. Furthermore, in his opinion, “fire is a menace, which should be prevented and suppressed.” Clearly, the blinkered view of fires in Africa are deeply rooted in the psyche of the silviculturist.

A review of fire literature not only reveals this dichotomy between policy and practise – which is neither new nor unique to fire, but it also points to a deeper problem that needs to be addressed before the fire “problem” can be resolved: the disagreement between the ecologists and the foresters. There are many internet articles and emotive newspaper reports that blame fires for destroying this and degrading that and threatening something else. That fires are a threat to human lives and property cannot be denied. However, there are very few (contemporary) peer reviewed research papers which corroborate the negative ecological effects of savanna fires. Nevertheless, this perception of fire as something bad that needs to be eradicated is so strong, that an entire nation will endeavour to suppress fire it at all costs. Such was the case in Finland, where changes in fire policies, improved fire fighting techniques and equipment, as well as altered public attitudes resulted in the near total eradication of fire from Finnish forests since the mid 1960’s (Vanha-Majamaa et al, 2004). This “success story” became an export product, and the Namibia-Finland Forestry Programme turned into a tool whereby a strategy that worked in the silviculture industry in one country, had to be applied to the dry savanna woodlands of another. How ironic then, that at about the same time when Finnish ecologists were grappling with the complexities of re-introducing fire to the forests of Finland (Vanha-Majamaa et al 2004, Hovi et al 2007), Finnish foresters were drafting a policy that would seek to eradicate fire from the Namibian environment.
2.3 Fire ecology and fire information

Over the last decade, fire has come to the forefront as an essential ecosystem process in African savannas. The vital role that seasonal burning plays in actually mitigating the destructive force of wildfires, protecting woodland and forest patches, increasing landscape heterogeneity and maintaining biodiversity, has been highlighted by a range of workers in the field (e.g. Parr and Brockett 1999, Laris 2002, Laris and Wardell 2006, Wardell-Johnson et al 2006, Andersen 2006, Parr and Eriksen 2007, Russell-Smith and Yates 2007, Bird et al 2008).

This benevolent effect relies on fires of low severity. The severity of a fire is distinct from ecosystem responses to the event (figure 2.3.1) and refers to the loss of, or damage to organic matter caused by the fire (Keeley, 2009). Fire severity is determined largely by fire intensity, burning frequency, seasonality and fuel load (Trollope 1982, Trollope 1984, Frost and Robertson 1985).

Some important woodland tree species such as Zambezi Teak (*Baikiaea plurijuga*) are fire sensitive, particularly after prior damage by frost, wildlife or people (Holdo, 2005). Frequent intense fires may change a mature Teak woodland into a shrub dominated landscape with only the skeletons of tall trees remaining, as described by Mendelsohnn and el Obeid (2005) (figure 2.3.2). Mature specimens of other equally important tree
species such as Burkea (*Burkea africana*) and Kiaat (*Pterocarpus angolensis*) are fire tolerant (Boughey 1963, Burke 2006) and are only threatened during the seedling recruitment phase (Curtis and Mannheimer 2005).

Burning frequency is a factor in determining fuel load, because regular burning reduces fuel build-up. Seasonality is a factor in fire intensity, because the time of year influences climatic variables that play an important role in fire intensity. Fireline intensity, defined as the heat released per second from a section of fuel 1m wide and extending from the front to the back of the flame zone (Byram 1973) is the main factor that determines the impact of fires in Namibia, because it is significantly correlated with vegetation response to fire in African savannas (Trollope and Tainton 1986, Trollope et al 2002).

Fireline intensity ($I$) can also be described as the rate of heat transfer per unit length of the fireline, and expressed in kWm$^{-1}$ is calculated using the formula

$$I = Hrw$$

*Equation 2-1*

where,

- $H$ = heat yield of fuel (Jg$^{-1}$)
- $r$ = spread (ms$^{-1}$)
- $w$ = fuel consumed (gm$^{-2}$)

*Figure 2.3.2. Ecosystem response to severe fire events in Zambezi Teak woodlands in northern Namibia. (Reproduced from Mendelsohn and el Obeid 2005. With permission)*
It is clear from this simple multiplicative equation, that an increase in any of the variables (H, r or w) will cause an increase in the intensity of the fireline, and therefore the impact that the fire has on the vegetation. What is not obvious, is the relationship between the variables, and how a change in one affects the other and therefore the final outcome.

The heat yield (H) of fuel is affected by a number of factors, but Trollope et al. (2004) gives recommended values for grass fuels in African savannas of 16 890 kJ/kg for headfires and 17 781 kJ/kg for backfires. The rate of spread (r) is influenced by fuel arrangement, condition, type, and load, as well as local weather conditions and has the greatest range of the three factors in the equation (Stocks et al 1997). Combustion will be slower in compacted, cold, heavy (coarse) fuels with a high moisture content, while a continuous layer of high fuel loads will accelerate combustion and increase the rate of spread. High air temperatures, low relative humidity and windy conditions all have a positive effect on the rate of spread, because it increases the drying rate of the fuel, and supplies oxygen to the combustion process (Trollope et al. 2004). The amount of fuel available or fuel load, expressed as the mass of the potentially combustible (i.e. dry) material per unit area, is a good indicator of fuel consumed (w), and is the only variable over which man has any control and which is directly affected by land use.

The importance of fuel load in determining fire intensity was highlighted by Heikkilä et al (2007), who pointed out that in grass fuels which typically make up the bulk of savanna fuel beds, the rate of spread will increase threefold when the fuel load doubles, thereby increasing the fire intensity by a factor of 6. Similarly, an increase in wind speed of 4 ms$^{-1}$ will more than double the rate of spread of a fire across fine fuels such as grass, with a corresponding increase in fire intensity for the same fuel load. Taking all these factors into account, fire intensity may range from 10 to >100 000 kWm$^{-1}$, although in African savannas the range is much smaller, with the maximum attainable intensity probably staying below 20 000 kWm$^{-1}$ (Stocks et al 1997).

The most favourable conditions for low severity fires would therefore be during cool, moist periods with little or no wind, when fuels still contain some moisture and loads are low. In the fire prone parts of Namibia, these conditions occur during autumn and early winter, while early summer is characterised by high air temperatures, high wind
speeds, and low fuel moisture. In order to understand observed structural and floristic changes in the savanna woodlands, it becomes necessary to understand past and present fire regimes – the question of when and where does it burn. Only when this information is at hand, can fully informed decisions be made on the formulation of a veld and forest fire policy.

2.4 Summary

Earth is a fire planet. The three elements of combustion have been present for sufficiently long, that biomass burning can be dated back to more than 450 million years ago. Anthropogenic biomass burning has been occurring for at least 400 000 years, and probably originated on what is now the continent of Africa. Despite this antiquity, it required only a few decades of colonial rule to entrench a deep seated resentment of forest fires in the psyche of African Administrators. This attitude lives on in post-colonial Africa, where it is enshrined in, and preserved through, legislation and policies which are generally out of touch with the reality of daily land management practices in rural areas. The ineffectiveness of these policies is evidenced by the fact that Africa remains the most fire prone continent in the world.

Many (anti) fire policies are developed in an information vacuum, or are misinformed by sweeping generalisations regarding the effects of fire on valuable natural resources. An overwhelming body of scientific evidence now exists, that shows fire as an essential ecosystem component that needs to be understood, embraced and applied judiciously, rather than dismissed out of hand and legislated out of existence.
3 MAPPING — A QUESTION OF SCALE

3.1 Introduction

Scale is usually defined as the ratio between a distance or size of an object on a map and the corresponding distance or size of the object on the ground (Wade and Sommer 2006). The reference to the word “map” links this definition to the traditional use of the word, i.e. cartography, but Goodchild (2001) argued that this paper map meaning does not make the transition to digital mapping applications, and suggested that this ratio – the representative fraction - be replaced by spatial extent and spatial resolution as primary metrics. Nevertheless, there are several other meanings that have been used in other disciplines.

In terms of remote sensing applications, scale can be applicable to the spatial domain as well as the temporal domain, or a combination of the two. Within the spatial domain, scale can apply to cartography as defined above; it can refer to geography where it relates to the area covered; it can apply to the scale at which natural processes operate, and it can apply to the smallest object that can be distinguished. These meanings are often interlinked, as in the case of burned area detection where the pixel size (measurement scale) can range from a few metres to more than a kilometre, but it requires many pixels to map the area burned (operational scale) during one fire savanna fire event. These interrelationships are illustrated in figure 3.1.1.

There are several potentially problematic issues related to scale in remote sensing studies. Cao and Lam (1997) list the following: the modifiable aerial unit problem, the ecological fallacy problem, and the problem of selecting imagery with the most efficient combination of scale and resolution. Any remote sensing study will have to address these issues in order to avoid substantive errors.
3.2 The Modifiable Areal Unit Problem

The MAUP is the fundamental geographical issue that affects any study that relies on spatially aggregated data (Cao and Lam 1997). It is defined as the problem that results from imposing artificial units of spatial reporting on continuous geographical phenomena, resulting in the generation of artificial spatial patterns (Heywood 1998). The MAUP was examined in detail by Openshaw (1984) who found that it was composed of two distinct but inter-related problems: a problem of scale which arises when data from a single set of areal units are resampled into larger units, and a problem of aggregation which arises when different aggregation methods are used to resample areal units into larger units.

In Remote Sensing, the areal unit is represented by the pixels of the image (Jelinski and Wu 1996). The first of Openshaw’s problems would therefore relate to the instantaneous field of view of different sensors which yield different spatial resolutions and therefore different pixel sizes in the image. Statistics generated from Landsat Thematic Mapper data are likely to differ from statistics obtained from MODIS data for the same area of interest, because of the different pixel sizes. These differences are illustrated in figure 3.2.1.
The second problem relates to the resampling method when aggregating pixels into larger units. Using a 3x3 pixel moving window, the resulting image would be quite different if the new (aggregated) pixel values are derived from the mean value of the nine pixels in the window, or if the value of the nearest neighbouring pixel is assigned to the new pixel. These differences are illustrated in figure 3.2.2. The nearest neighbour operation has the advantage that it is computationally simple and retains original data values. It is therefore often used when digital classifications are to be performed on the resampled data. Pixel aggregation yields a visually pleasing image because of the smoothing effect of the averaging operation, at the expense of

Figure 3.2.1 MODIS false colour composite (RGB=7,2,1) imagettes of the same geographical area, but at 250 m (A), 500 m (B), 1000 m (C) and 2000 m (D) pixel size. The dark brown areas are recent burn scars. The dark green diagonal line across the lower left of the images is caused by dense vegetation along the banks of a perennial river. The bright orange spot to the right of the river is an active fire. Areal statistics derived from the four images are likely to differ significantly.
(Data courtesy of NASA/GSFC, MODIS Rapid Response)
producing new data values. It is best used for studies which rely on visual interpretation of the image. Various refinements to these resampling techniques have been developed, such as bilinear interpolation and cubic convolution.

![Figure 3.2.2 MODIS false colour composite (RGB=7,2,1) imagettes of the same geographical area – the Etosha Pan in northern Namibia. Image A is at the original 250 m pixel size. The other two images show the results of resampling operations performed on image A. Both have been resampled to 1000 m pixels, but using different methods. Image B was produced by a nearest neighbour operation, while image C is the result of pixel aggregation. (Data courtesy of NASA/GSFC, MODIS Rapid Response)](image)

3.3 The ecological fallacy problem

The ecological fallacy lies in the assumption that fine resolution (micro or individual level) relationships can be inferred from coarse resolution (macro or aggregate level) analyses. Openshaw (1984b) found that this problem was endemic, but not unique, to areal census (e.g. aircraft based game/wildlife surveys) data. He concluded that it was not possible to predict the severity of the problem with respect to particular variables and particular techniques. It is therefore important to be aware of the possibility that relationships observed at one scale may not be statistically significant at a different level of analysis. Careful consideration should therefore be given to the selection of appropriate areal units for a particular study or analysis. In practice, the selection of areal units (pixel size) in Remote Sensing studies is often determined by external factors that require a certain amount of compromise from the analyst. These factors are discussed in more detail in the following section.
3.4 The problem of selecting optimum imagery

The study of burned area and the factors that influence the extent and timing of fires are affected by events that fall within either the temporal or spatial domains, or a combination of the two. Within the temporal domain, rainy seasons and the accompanying growing periods last for several months. Similarly, the dry season which allows the new growth to dry and cure into fine fuels can be measured on a scale of months. Actual fire events however, are usually of much shorter duration, ranging from mere hours to a few weeks at most.

Within the spatial domain, the burned area that results from a discrete fire event in the savanna regions of Namibia can vary in size from less than one hectare, to several hundred thousand hectares. Under normal circumstances, these events give rise to burned areas that are commensurate with the duration of the burn – a fire event of short duration is likely to burn a smaller area than a fire that rages for days or weeks, thereby giving savanna fires a spatio-temporal dimension. The different biophysical parameters and the domains that they occupy are illustrated graphically in figure 3.4.1.

The case for using satellite imagery to quantify burned areas, not only in African savannas but around the world, has been made by a multitude of studies over the last few decades (Langaas 1992, Cahoon et. al. 1992, Scholes et. al. 1996, Justice et. al. 2002, Eva and Lambin 1998, Barbosa et. al. 1999, Dwyer et. al. 2000, Tansey 2002, Nielsen et. al. 2002, Boschetti et. al. 2004, Silva et. al. 2005). The spatio-temporal variability of fire events makes the appropriate choice of imagery both difficult and essential, because imagery that is optimal for the measurement of one variable may not be suitable for another.

Imagery from different sensors will have different spatio-temporal scales, as shown in figure 3.4.2. Ultimately, the optimal scale of imagery for any remote sensing study will be determined by the information that is required about the ground scene, the methods to be used for extracting this information from the image, and the spatial structure of the actual scene (Woodcock and Strahler 1987).
Figure 3.4.1 Diagrammatic representation of the spatio-temporal scales of African savannas and the capabilities of the NOAA AVHRR data, with the domains of plant biomass production and burning overlain. (After Graetz 1987)
Minimum mapping units are traditionally defined as the smallest surface area permitted for any polygon (Villa et al 2008). For studies that rely on visual interpretation of satellite imagery, this lower limit is set by the spatial resolution of the sensor. Although many studies have demonstrated techniques for extracting sub-pixel information from imagery (Cross et al 1991, Foody and Cox 1994, Ju et al 2003, Thenkabail et al 2007, Boucher 2009), they are by and large a means of dealing with mixed pixels rather than a way of delineating the boundaries of a discrete entity which is smaller than one pixel. Mixed pixels commonly occur in heterogeneous subjects scanned by low or medium resolution sensors such as AVHRR or MODIS.

For the delineation of burned areas, this study relied on computer assisted visual interpretation of the satellite images. The minimum mapping unit therefore remained equal to the data resolution of the original imagery. The actual geospatial unit at which data analysis was conducted and which represents the maximum level of data aggregation, corresponds to a quarter degree square (QDS), and the maps which present the analytical model outputs from this study use the QDS as a geospatial mapping unit. The QDS was described by Edwards and Leistner (1971) as a means of recording the locality of biological specimens and remains a commonly used geocoding method in African biodiversity mapping. Many studies have demonstrated the linkages between biodiversity and savanna fires (Parr and Brockett 1999, Laris 2002, Parr and Andersen 2006, Wardell-Johnson et al 2006, Bird et al 2008) The decision was
therefore taken to analyse data from this study at a comparable scale, and to present findings in a format that would eventually allow comparisons between biomass production/biomass burning and biodiversity parameters.

The QDS was adopted by field biologists in favour of actual coordinate level georeferences, because of the fear that the precise nature of the latter might compromise endangered or sensitive species. As the name implies, the quarter degree square is a form of geocoding that is obtained from recursive division of a degree square formed by intersecting parallels and meridians. The system used in this study follows the southern African naming convention, whereby every QDS is labelled with a 6 digit code as follows: each degree square is designated by a four-digit number made up of the values of intersecting latitude and longitude at its top left corner, e.g. 2217 for the grid cell that contains Windhoek in central Namibia. This degree square is then divided into four "half degree squares", each 30' x 30' in size. The squares are labelled A, B, C and D, and these letters are suffixed to the degree square number. Windhoek would therefore be in “half degree square” 2217C. Each half degree square is then divided and labelled in this way to form QDSquares of 15' x 15' in size. Windhoek is now in QDS 2217 Ca. An example of this process is given in figure 3.5.1.

Namibia is covered by 1300 QDSquares, each approximately 25 x 25 km in size. The system as currently used in Southern Africa does not provide unique references across
the Equator and Prime Meridian. Larsen et al (2009) addressed this issue, and proposed an extended QDGC (quarter degree grid cell) based on the original QDS for use as a standard, scalable means of sharing biodiversity information across the African continent.

3.6 Summary

With the move from paper maps to digital computer displays with its infinitely variable “zoom” options, the definition of scale has acquired new meaning. It has therefore been suggested that the traditional ‘representative fraction’ be replaced by a combination of spatial extent and spatial resolution as the main means of defining the scale of digital map products.

Within the spatio-temporal domain of Remote Sensing, scale can refer to objects, disciplines and or processes. This leads to a number of factors that need to be considered during the selecting, analysis and interpretation of remotely sensed data. Of these, the modifiable areal unit problem (MAUP), the ecological fallacy and the selection of optimal imagery, are the most prominent.

The MAUP arises when different spatial units are chosen for a particular analysis. In Remote Sensing these units are the pixels of the image. There are two interrelated issues when changing pixel size. Firstly, there are problems that arise when resampling any particular set of pixels into larger units, and secondly, these problems are complicated by the availability of different resampling methods which yield different results.

The ecological fallacy assumes that micro level ecosystem processes can be inferred from macro level data, and that the relationships will hold true regardless of the aggregation level. Careful consideration should therefore be given to the selection of imagery that is of an optimal scale for the processes that are being investigated.

The selection of optimal imagery is guided by the information that is required, the methods to be used for information extraction, and the spatial homogeneity or
heterogeneity of the study area. This choice is complicated by sensor limitations, in that high spatial resolution often equates to low temporal resolution, thereby confounding studies which require high spatio-temporal resolution data.

Minimum mapping units (MMU) usually refer to minimum polygon size. Anything smaller must be absorbed by a neighbouring class or object. In Remote Sensing, the MMU is no smaller than the data resolution. For the purpose of this study, and in order to make comparisons with existing biodiversity data, the MMU is a quarter degree square. This is equal to 15 minutes of latitude by 15 minutes of longitude in size, which in Namibia equates to an area of approximately 25 x 25 km in size.
"I have no data yet. It is a capital mistake to theorise before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

Sir Arthur Conan Doyle (1859-1930) - Sherlock Holmes in "A Scandal in Bohemia"

CHAPTER 4. SATELLITE DERIVED DATASETS – VEGETATION INDICES AND BURNED AREAS

4 SATELLITE DERIVED DATASETS – VEGETATION INDICES AND BURNED AREAS

4.1 NOAA AVHRR Data


First launched in June 1979 onboard NOAA 6, the AVHRR/2 is a five-channel, filter-wheel spectrometer/radiometer, with a scanning rate of 360 scans per minute. The system (AVHRR sensor and NOAA Satellite platform) characteristics are given in table 4-1. The satellites orbit the Earth 14 times each day at an altitude of approximately 833 km and provides data in a 2399 km wide swath.

AVHRR data are acquired in three formats:

- High Resolution Picture Transmission (HRPT)
- Local Area Coverage (LAC)
- Global Area Coverage (GAC)

HRPT data are full resolution image data that are not stored onboard, but are continuously transmitted in real-time to any ground stations within view of the satellite.
LAC is full resolution data that are recorded on an onboard tape for subsequent transmission during a station overpass. The average instantaneous field-of-view of 1.4 milliradians yields a HRPT and LAC ground resolution of approximately 1.1 km at the satellite nadir from the nominal orbital altitude. GAC data are derived from onboard averaging of the full resolution AVHRR data. Four out of every five samples along the scan line are used to compute one average value and the data from only every third scan line are processed, yielding 1.1 km by 4 km resolution at the subpoint. GAC data are for readout by Command and Data Acquisition (CDA) stations only (NOAA/NESDIS 1998).

<table>
<thead>
<tr>
<th>Sensor Characteristics</th>
<th>Spectral Bandwidth</th>
<th>Radiometric Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel 1:</td>
<td>0.58 to 0.68 μm</td>
<td>10 bits</td>
</tr>
<tr>
<td>Channel 2:</td>
<td>0.725 to 1.10 μm</td>
<td>1024 levels</td>
</tr>
<tr>
<td>Channel 3:</td>
<td>3.55 to 3.93 μm</td>
<td></td>
</tr>
<tr>
<td>Channel 4:</td>
<td>10.3 to 11.3 μm</td>
<td></td>
</tr>
<tr>
<td>Channel 5:</td>
<td>11.5 to 12.5 μm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Visible (red)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reflected near-infrared</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hybrid reflected / thermal infrared</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal infrared</td>
<td></td>
</tr>
</tbody>
</table>

| Instantaneous field of view (IFOV) | 1.30 to 1.51 milliradians depending on the channel | Yielding ≈ 1.1 km ground resolution at nadir |

| View angle | 55.4° | Yielding ≈ 6 km ground resolution at edge of swath |

| Swath Width | ≈ 2400 km |

<table>
<thead>
<tr>
<th>Platform Characteristics</th>
<th>Orbit</th>
<th>Near-polar, Sun-synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>833 to 870 km</td>
<td></td>
</tr>
<tr>
<td>Orbital period</td>
<td>102 minutes</td>
<td></td>
</tr>
<tr>
<td>Equatorial crossing time</td>
<td>07h30 and 19h30 Even numbered satellites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14h00 and 02h00 Odd numbered satellites</td>
<td></td>
</tr>
<tr>
<td>Repeat cycle</td>
<td>12 hours</td>
<td></td>
</tr>
<tr>
<td>Global coverage</td>
<td>1 to 2 days</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-1 Summary of NOAA AVHRR system characteristics(NOAA/NESDIS 1998)
4.2 Direct Reception in Namibia

AVHRR HRPT data reception in Namibia started at the Etosha Ecological Institute in 1993, with the installation of a receiving station as part of the Natural Resources Institute (NRI) initiative of Local Applications of Remote Sensing Techniques (LARST), funded by the British Overseas Development Agency (ODA). The aim of this initiative was to promote improved management of natural resources through real-time decisions based on locally received and processed cost-effective Remote Sensing.

The receiving system was developed by Bradford University Remote Sensing Ltd. (BURS) and pre-processing of the raw HRPT data was done using their MS® DOS™ based software. Post processing was done using IDRISI1 for DOS™. All pre and post processing routines were accomplished through locally developed batch routines (appendix 1). The BURS system creates data blocks (appendix 2) within the file for a particular overpass, and as a result, the files generated by the system are referred to as blockfiles. The initial manually operated satellite tracking/data reception (figure 4.2.1) and DOS based routines were later upgraded to a fully automated PC driven tracking/reception and MS® Windows™ based NOAA Operations Manager (NOM) software. The system collected data over a 10 year period – double the anticipated lifespan of the project, and five years beyond funded support.

Blockfiles and calibrated channel images were archived routinely, but at varying intensities depending on contemporary policy. Initially, storage space placed a limit on the archive, with data initially being stored on magnetic tape and later on 3.5" Magneto-optical (MO) disks with a capacity of 128 MB (64 MB on each side.

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1 IDRISI GIS and Image Processing software. Clark Labs, Clark University, Worcester, MA, USA.
of the disk). Blockfiles that cover the entire country are approximately 25-28 MB in size, and with one daytime and one night-time image being collected every day, an MO disk would be filled with blockfiles every 2-2½ days. Archiving at full intensity would therefore require about 150-180 MO disks every year. During the 1990’s, a 128 MB disk represented state of the art external storage and prices were high. Even today, such disks remain relatively expensive with prices for 128 MB Verbatim MO disks at around €8.00 per disk. As a consequence, blockfiles were archived selectively, based on institutional focus and availability of funds, but generally at an intensity of several cloud free images that cover Namibia per month. This frequency increased steadily with the advent of recordable CD’s. Calibrated channel images were produced routinely and stored on CD. Historical datasets were back processed into calibrated channel images and added to the CD archive, and the blockfile archive was transferred to CD in order to facilitate access to the data.

4.3 Data Pre-processing

Pre-processing of satellite image data is usually a two-stage process, and involves:

1. Geometric correction, whereby the raw data are corrected for geometric distortions and locational information added by using the orbital record and image acquisition geometry.

2. Calibration, whereby the raw quantised digital numbers are converted into physical values such as % reflectance, radiance or brightness temperatures as originally observed by the sensor.

In some cases, image acquisition problems arose which could not be addressed by pre or post processing. The system did not always capture perfect images and in the worst cases, entire blocks of scan lines were filled with random noise. It is impossible to patch these errors with the original data, in the absence of a duplicate image captured by another system located elsewhere. An example of a raw AVHRR image exhibiting this problem is shown in figure 4.3.1. This problem did not affect the production of burned area data for this study, as it was possible to select from several unaffected images every month. Vegetation index imagery was severely affected however, limiting their utility to areas in and around the Etosha National Park.
4.3.1 Geometric correction

Images from the AVHRR were received in Satellite Projection, also referred to as the General Perspective Projection, which represents a view of the globe as seen from a camera in space. This view can be easily visualised by tilting a Google Earth image (figure 4.3.2). Orthographic, stereographic, and gnomonic projections are special cases of this projection. The area directly under the satellite (nadir) appears in great detail, but due to the wide swath covered by the sensor, and the curvature of the Earth, points towards the edges of the image become distorted with a corresponding loss of detail.

Figure 4.3.1  Calibrated AVHRR HRPT Channel 2 reflectance image of Namibia acquired from NOAA 14 at 13:16:58 GMT on 25/08/1997, showing 3 broad bands of random noise.
Geometric correction of this projection proves challenging to conventional methods, due to the variable distortion across the image. It is therefore achieved by:

1. Navigating the image and attaching Latitude and Longitude tie points for every 32 pixels along every 16 lines, using a NOAA satellite orbital model and image capture geometry. Pixel locations between sample points are derived from bilinear interpolation (NRI Undated). The image remains in satellite projection.
2. Using the tie point data to reproject the image into a desired projection, such as Universal Transverse Mercator or Plate Carrée.

4.3.2 Calibration

Calibration of the AVHRR data using the NOM is a two step process which involves:

1. Calibrating DNs for all 5 Channels into Radiance values
2. Transforming Radiance values for Channels 1 & 2 to percentage Reflectance and converting Radiance to Brightness Temperatures for Channels 3, 4 & 5.

The NOM strives to maintain the original 10 bit radiometric resolution of the AVHRR data.

There is a linear relationship between the DNs quantised by the sensor, and the Top of the Atmosphere Bi-directional Reflectance Factor (hereafter referred to as Reflectance). It is therefore possible to convert the DNs for the visible channels 1 and 2...
into Radiance values using a simple linear equation such as given in equation 4-1 and described by Holben et al (1990).

\[ L_i = \alpha_i (D_i - D_{oi}) \]  
*Equation 4-1*

Where \( i = \) Channels 1 & 2

and

\( L_i \) = Radiance for channel \( i \) in Wm\(^2\)sr\(^{-1}\) μm\(^{-1}\)
\( D_i \) = DN for Channel \( i \) in 10 bit counts
\( D_{oi} \) = Offset for Channel \( i \) in 10 bit counts
\( \alpha_i \) = Gain for Channel \( i \) in Wm\(^2\)sr\(^{-1}\) μm\(^{-1}\)count\(^{-1}\)

Because the NOM first calibrates into radiance and then converts the radiance values to reflectance, the calibration is defined in terms of Offset and Gain coefficients \( D_{oi} \) and \( \alpha_i \) in equation 4-1. There is no onboard calibration of the Channels 1 and 2 sensors, and pre-launch calibration coefficients do not yield accurate results due to changes in sensor gain sensitivity over time. During conversion from DNs to Radiance, the values for \( D_{oi} \) and \( \alpha_i \) are retrieved from a lookup table in the NOM, developed from time dependant equations designed by Rao and Chen (1996).

The transformation of Radiance into percentage Reflectance is given by:

\[ \rho_i = 100 \times \frac{\pi L_i d^2}{E_{ui} \cos \theta} \]  
*Equation 4-2*

Where \( i = \) Channels 1 & 2

and

\( \rho_i \) = Top of the Atmosphere Bi-directional Reflectance Factor for channel \( i \) in %
\( E_{ui} \) = Equivalent exo-atmospheric solar irradiance for channel \( i \) in Wm\(^2\)μm\(^{-1}\)
\( \theta \) = Solar zenith angle in decimal degrees from vertical
\( L_i \) = Radiance for channel \( i \) in Wm\(^2\)sr\(^{-1}\)μm\(^{-1}\)
\( d \) = Sun-Earth distance in Astronomical Units
Calibration coefficients for the thermal channels 3, 4 and 5 are derived onboard the satellite and transmitted as part of the data stream. Using these coefficients, it is possible to perform a linear calibration following a three step operation as described in the NOAA Polar Orbiter Data (POD) User's Guide (Kidwell 1995):

1. Compute a linear gain and intercept based on the instrument count of space and internal blackbody
2. Apply the slope and intercept to calculate scene radiance
3. Convert the radiance to brightness temperature using the Plank functions

In the NOM, gain and intercept is computed using the following two equations:

\[
\alpha_i = \frac{(L_u^i - L_q^i)}{(D_u^i - D_q^i)} \quad \text{Equation 4-3}
\]

\[
\beta_i = L_u^i - \alpha_i D_u^i \quad \text{Equation 4-4}
\]

Where \( i \) = Channels 3, 4 & 5

and

\( \alpha_i \) = Gain for Channel \( i \) in Wm\(^2\)sr\(^{-1}\)μm\(^{-1}\)count\(^{-1}\)

\( L_u^i \) = Radiance of onboard target for channel \( i \) in Wm\(^2\)sr\(^{-1}\)μm\(^{-1}\)

\( L_u^* \) = Radiance of deep space for channel \( i \) in Wm\(^2\)sr\(^{-1}\)μm\(^{-1}\)

\( D_u^i \) = Digital counts of onboard target for channel \( i \)

\( D_u^i \) = Calibration offset coefficient for channel \( i \) in digital counts

\( \beta_i \) = Intercept for channel \( i \) (no units)

From these gain and intercept coefficients, a linear scene Radiance is computed using:

\[
L_{\text{lin}}^i = \alpha_i D_i - \beta_i \quad \text{Equation 4-5}
\]

Where:

\( L_{\text{lin}}^i \) = Linear Radiance for channel \( i \) in Wm\(^2\)sr\(^{-1}\)μm\(^{-1}\)

\( D_i \) = DNs channel \( i \) in 10 bit counts
The NOM calibration implementation then converts the Radiance values into Brightness Temperatures using an integrated response curve as recommended by the European Space Agency (NRI Undated). The integration is performed in discrete steps for the spectral response function:

\[
L^*_i(T_i) = \sum_{n=0}^{59} \beta(v_{i,n}, T_i) \phi(v_{i,n}) \quad \text{for } i = \text{channels 3, 4 and 5.} \quad \text{Equation 4-6}
\]

Where \( \beta(v_{i,n}, T_i) \) is Plank’s function for a blackbody:

\[
\beta(v_{i,n}, T_i) = \frac{C_1(v_{i,n})^3}{(e^{(C_2(v_{i,n})/T_i)} - 1)} \quad \text{in Wm}^{-2}\text{sr}^{-1}\text{cm} \quad \text{Equation 4-7}
\]

and

\[
v_{i,n} = v_{1i} + n\delta v_i \quad \text{in cm}^{-1} \quad \text{Equation 4-8}
\]

- \( v_{i,n} \) = Wave number in the spectral bandwidth of channel \( i \) in cm\(^{-1}\)
- \( v_{1i} \) = Starting wave number of channel \( i \) in cm\(^{-1}\)
- \( \delta v_i \) = Wave number increment for channel \( i \) in cm\(^{-1}\)
- \( \phi(v_{i,n}) \) = Band \( i \) spectral response function at wave number \( v_{i,n} \)
- \( T_i \) = Band \( i \) brightness temperature in Kelvin
- \( C_1 = 1.1910659 \times 10^{-5} \) in mWm\(^{-2}\) sr\(^{-1}\)cm\(^4\)
- \( C_2 = 1.438833 \) in Kcm
4.4 Vegetation Index Data

There are many different biophysical metrics that can be derived from remotely sensed data. Of all the methods that have been developed to detect photosynthetic activity in plants, the Normalised Difference Vegetation Index (NDVI) is possibly the most enduring, and has been widely used not only to derive plant biomass estimations (e.g. Sannier et al 2002), but also for crop yield forecasting (e.g. Sannier 1999), rangeland condition monitoring (e.g. Prince & Astle 1986), evaluation of land performance (e.g. Li et al 2004) and landscape degradation (e.g. Holm et al 2003), drought forecasting (e.g. Kassa 1999), land cover classification (e.g. DeFries & Townshend 1994), as well as burned area mapping (e.g. Kasischke et al 1993).

The NDVI employs a simple red/near-infrared ratio, based on the fact that the chlorophyll cells of actively growing (green) plants absorb solar radiation in the photosynthetically active radiation (PAR) spectral region in order to provide energy for photosynthesis. At the same time, solar radiation in the near-infrared (NIR) spectral region is strongly reflected by growing plant cells to prevent over-heating and possible tissue damage. As a result, actively growing plants appear relatively dark in the PAR and relatively bright in the NIR region as shown in figure 4.4.1.

![Image of the typical "Peak and Valley" spectral response curve of actively growing vegetation.](image-url)
Using the AVHRR channels 1 and 2 data, acquired in the red and near-infrared parts of the spectrum, the NDVI is calculated from:

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$  \hspace{1cm} Equation 4-9

Where:
- \(R\) = Spectral reflectance values for Channel 1 (red)
- \(NIR\) = Spectral reflectance values for Channel 2 (near-infrared)

Spectral reflectance is already a ratio of the reflected radiation over incoming radiation in each spectral band (equation 4-2), with potential values ranging between 0.0 and 1.0. As a consequence, NDVI values range between -1.0 and +1.0. The normalisation of this simple equation is designed to account for (i.e. “normalise”) the effects of seasonal changes in solar zenith angles on the recorded reflectance values.

NDVI images are usually composited into 10-daily or bi-monthly maximum value images, in order to:
- Reduce the effect of signal attenuation from water vapour and aerosols in the atmosphere
- Reduce the effect of edge of swath distortion
- Reduce the effect of directional reflectance
- Minimise sun-angle and shadow effects
- Reduce cloud contamination

The technique was described by Holben (1986) who found that an example from Southern Africa showed an increase of 40 per cent from individual image values to the final composite image.
4.4.1 NDVI Data Sets for Namibia

NDVI images for Namibia were produced routinely from direct reception NOAA AVHRR HRPT data captured at the Etosha Ecological Institute. Daily images were composited into dekadal maximum value composite (MVC) images and archived on CD. The Institute therefore houses an archive of NDVI data spanning a 10 year period between 1994 and 2003 at a spatial resolution of 1 km and geographic coverage that includes the entire country. These data are unique for this time period and geographic coverage, because there is no global coverage of AVHRR data at 1 km resolution. As mentioned in section 4.1, HRPT data are not stored onboard the satellite. The only means of obtaining such data is by prior arrangement with NOAA, or by direct reception through a local receiving station such as the one operated by the Etosha Ecological Institute.

Vegetation photosynthetic activity in Namibia is largely confined to the rainy season. Clouds which cover large parts of the country during this time of the year are opaque to sensors in the visible and NIR part of the spectrum. Cloud affected areas and obvious cloud shadows are therefore masked out of the image, leaving areas that are essentially holes in the data and that are usually flagged as “cloud” or “no data” and assigned a high negative NDVI value such as -1. These holes are filled with data from subsequent images during the compilation of the maximum value composite images. Images that are almost totally cloud covered were not considered for processing and during the early years, the Blockfiles were discarded to economise on storage.

The dynamic nature of plant photosynthetic activity places constraints on the minimum number of daily images that are used in the compositing process for a particular dekad. Extracting maximum NDVI values from only one or two images collected at the start or end of a 10 day period often resulted in a false step in NDVI values when comparing that particular MVC image with the preceding or subsequent MVC. For the purpose of illustration, NDVI values for 1 pixel over an idealised 30 day period where plants are greening up at a steady rate are presented in table 4-2.
Table 4.2  Idealised NDVI values for a 30 day period.

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
<th>Day 5</th>
<th>Day 6</th>
<th>Day 7</th>
<th>Day 8</th>
<th>Day 9</th>
<th>Day 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21</td>
<td>0.22</td>
<td>0.23</td>
<td>0.24</td>
<td>0.25</td>
<td>0.26</td>
<td>0.27</td>
<td>0.28</td>
<td>0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>0.31</td>
<td>0.32</td>
<td>0.33</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td>0.37</td>
<td>0.38</td>
<td>0.39</td>
<td>0.40</td>
</tr>
<tr>
<td>0.41</td>
<td>0.42</td>
<td>0.43</td>
<td>0.44</td>
<td>0.45</td>
<td>0.46</td>
<td>0.47</td>
<td>0.48</td>
<td>0.49</td>
<td>0.50</td>
</tr>
</tbody>
</table>

If these data are used to extract maximum dekadal values, it would ordinarily yield:

Dekad 1 = 0.3  Dekad 2 = 0.4 and Dekad 3 = 0.5  \(\text{Scenario/Series 1}\)

However, if during the 2\textsuperscript{nd} dekad, all the values after Day 11 had to be discarded due to cloud contamination, the maximum dekadal values would be:

Dekad 1 = 0.3  Dekad 2 = 0.31 and Dekad 3 = 0.5  \(\text{Scenario/Series 2}\)

Similarly, if values from Day 22 onwards could not be used, the maximum dekadal values would be:

Dekad 1 = 0.3  Dekad 2 = 0.4 and Dekad 3 = 0.41  \(\text{Scenario/Series 3}\)

When data from these three scenarios, generated from one set of data are analysed, each gives a very different picture as regards the progression of the greening up, as shown in figure 4.4.2. The straight blue line from Series 1 in the Graph represents the actual greening up progression. Series two seems to indicate a sudden acceleration in the greening up, possibly as a result of a rain shower over grassland? Series 3 seems to indicate a decline in photosynthetic activity, possibly indicating a dry spell. For this reason, the tendency is to include as many daily

Figure 4.4.2  Idealised representation of NDVI progression, to illustrate the effect of input image selection during the MVC production process.
NDVI images into the MVC production process as possible. As a consequence, sub-optimal imagery is sometimes included in the belief that it will enhance the end product. While this might be the case for contaminated pixels of low value, the problem of large blocks of noise in the raw data, as mentioned in section 1.3 and shown in figure 4.3.1, can cause erroneously high NDVI values which are perpetuated in the MVC image. The result is a banding effect which persists even when cumulative MVC images are produced for the season (figure 4.4.3). This problem was not considered critical for studies conducted inside the Etosha National Park, but detracts from the value of a national data set.

For this reason, AVHRR NDVI data from the Global Inventory Modelling and Mapping Studies (GIMMS) collection was used. This product is available for a 25 year period from 1981 to 2006. The data set is derived from imagery obtained from the AVHRR instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17 and has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change (Tucker et al 2004, Pinzon et al 2005, Tucker et al 2005). The source for the data was the Global Land Cover Facility (GLCF), www.landcover.org. The data are provided in the original 8km GAC data resolution reprojected to an Albers Equal Area Conic projection using the Clarke 1866 ellipsoid. Images are composited at a 15-day time step, where the first composite (15a) is the MVC from the first 15 days of the month, and the second (15b) is from days 16 to the end of the month. The raw data are 16-bit integer files, and the -1 to 1 range of NDVI needs to be recovered using the following formula: \[ \text{NDVI} = \frac{\text{raw}}{10000}/10. \]

A few alternative global NDVI data sets are available, but neither Pathfinder Project\(^2\) nor *Satellite Pour l’Observation de la Terre*\(^3\) (SPOT) data are available for the time period covered by this study or at the spatial resolution required. SPOT NDVI data are generally considered to be an improvement over AVHRR data, but a comparative study by Fensholt et al (2006) found an exact match in dynamic range between AVHRR GIMMS NDVI and SPOT-4 VGT NDVI, and high correlations between annually integrated values of AVHRR GIMMS and SPOT-4 VGT on a continental scale.

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\(^2\) [http://gcmd.nasa.gov/records/GCMD_EOSWEBSTER_NOAANASA_Path_NDVI.html](http://gcmd.nasa.gov/records/GCMD_EOSWEBSTER_NOAANASA_Path_NDVI.html)

\(^3\) [http://www.spotimage.com](http://www.spotimage.com)
Figure 4.4.3 Cumulative NDVI maximum value composite images for Namibia for six growing seasons, showing data integrity anomalies caused by banding in the original NDVI images used during the compositing process.
4.4.2 Phytophenological metrics

Phenology is generally described as “the art of observing the phases of the life cycle or the activities of plants and animals as they occur throughout the year” (Leith 1971). Plant phenological cycles play an important role in savanna fire studies as described in Chapter 2. Phytophenological milestones include the dates on which the growing season starts and ends (length of the growing season), which together with the strength of the growing season largely determines the quantity of biomass produced and therefore determines the potential fuel availability for savanna fires. Similarly, the start of the dry season is an important date, as fire severity is often defined by whether burning takes place early or late in the dry season. These dates are often based on climatological data, or are assigned arbitrarily based on casual observations, with very few studies (e.g. Nielsen & Rasmussen 2001) using remotely sensed data. It is however possible to retrieve a wide range of metrics directly from NDVI time series data, which can be used to define the phytophenological cycle with far greater accuracy. For this study, the following metrics were derived from the NDVI data for each QDS:

*Max NDVI:* The maximum NDVI value for the season provides an indication of the predominant vegetation type. For instance, long term (10 year) averaged maximum NDVI values for Namibian steppe/grassland for any given season are much lower than that of shrub- or high tree savanna areas (Sannier et al 1995).

*Mean NDVI:* The mean NDVI value is an indication of the relative greenness of the vegetation over the course of the season.

*NDVI Amplitude:* The amplitude of the NDVI values is an indication of the seasonality of the vegetation and, together with the maximum
NDVI, can provide an indication of the vegetation type. For instance, grassland would have a lower amplitude than deciduous woodland.

**NDVI Threshold (main green-up):** The NDVI Threshold marks the start of the growing season, and is defined as the time of the greatest increase in NDVI between 4 consecutive dates \( t, t_{+1}, t_{+2} \) and \( t_{+3} \). NDVI Threshold is taken to be the NDVI value at \( t \). Previous studies (e.g. DeFries et al 1995) used a less robust single step maximal increase between \( t \) and \( t_{+1} \). (a - Figure 4.4.4).

**Length of growing season**: The number of days between the start of the main growing season and the end of the growing season. (b - Figure 4.4.4).

**Length of green-up season:** The number of days between the start of the growing season and the maximum NDVI value. This value, together with the maximum NDVI, is used to determine the rate of green-up. (c - Figure 4.4.4).

**Length of senescing season:** The number of days between the maximum NDVI value and the end of the growing season. (d - Figure 4.4.4).

**Rate of green-up:** This metric gives the change in NDVI value during the green-up phase, and is

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4 The growing season includes the green-up and senescing periods
5 This study differentiates between gradual (initial) greening up and subsequent rapid (main) greening up.
expressed in NDVI units/day, calculated by dividing the difference between NDVI Max and NDVI threshold by the number of days in the green-up period.

**Rate of senescence:** This metric gives the change in NDVI value during the senescing phase, and is expressed in NDVI units/day, calculated by dividing the difference between NDVI Max and NDVI threshold at the end of the season by the number of days in the senescing period.

**Integrated NDVI for growing season:** The area under the curve, calculated as the sum of the values between the NDVI threshold and the end of the season. Together with the mean NDVI, this metric gives an indication of the total productivity during the season. (e - Figure 4.4.4).

**Month of max NDVI:** The month during which the maximum NDVI value is recorded.

**Month of (initial) season start:** The month during which the NDVI threshold is initially exceeded. (f - Figure 4.4.4).

**Month of (main) season start:** The month during which the sharpest sustained increase in NDVI values start, and the threshold exceeded as described for NDVI Threshold (main green-up) above. (g - Figure 4.4.4).
CHAPTER 4. SATELLITE DERIVED DATASETS – VEGETATION INDICES AND BURNT AREAS

**Month of season end:**

The month during which slope of the senescence curve levels off, defined as the time of the least sustained decrease in NDVI between 4 consecutive dates \( t, t_1, t_2 \) and \( t_3 \). This value is therefore not equal to the NDVI threshold as assumed by DeFries *et al* (1995), and is considered to be a more realistic approach. (h - Figure 4.4.4).

**Season skewness:**

This metric describes the shape of the growing season curve, expressed as a ratio of the month of max NDVI minus the month of season end, over the month of season end minus the month of max NDVI.

**Bimodal difference:**

This metric provides an indication of the period between the initial season start and the main season start, and is calculated by subtracting the initial start date from the main start date. A value of zero would indicate a unimodal season.

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Figure 4.4.4  Temporal profile of NDVI values for QDS 1916 Cd in central Namibia, to illustrate some of the main phenological metrics derived from fortnightly NDVI values:

a) NDVI Threshold (main green-up); b) Length of growing season;
c) Length of green-up season; d) Length of senescent season;
e) Integrated NDVI for growing season; f) Month of (initial) season start;
g) Month of (main) season start; h) Month of season end.
4.4.3 Methodology

GIMMS NDVI data for the ten year period spanning 1994 to 2003 were downloaded from the Global Land Cover Facility at the University of Maryland, USA. ftp://ftp.glcf.umd.edu/glcf/GIMMS/Albers/Africa/. The datasets consist of 15 day maximum value composite images in Albers Equal Area projection with 8 km pixel size and 16 bit pixel values, covering the continent of Africa. Using the Global Mapper® image processing software package, the Namibia study area was windowed out of each scene and exported as an 8 bit geotiff image in a geographic coordinate system to ensure compatibility with standard GIS software packages.

Each image was then converted to a grid using the ArcView® 3.3 GIS software package, and its Spatial Analyst™ 2.0a extension. The mean NDVI value for each QDS was calculated using the “summarise zones” function of Spatial Analyst and the Namibia QDS vector layer as input zones. These values for each 15 day period for each QDS were then added to a Microsoft® Excel™ table. In this way, a spreadsheet of values with 15-day time steps for a particular QDS was built up for a twelve month period. A spreadsheet tool was developed to extract the phytopenological metrics described in section 1.4.2. These metrics were then appended to the QDS vector layer database file, thereby allowing the visualisation of the spatial distribution of the phenological milestones as illustrated in figure 4.4.10. The workflow is illustrated in figure 4.4.5.

**Figure 4.4.5** A flow diagram illustrating the phytopenological metrics extraction and visualisation process.
4.4.4 Results

A section of the spreadsheet tool that was developed to extract the phytophenological metrics is shown in figure 4.4.6. On their own, the unprocessed NDVI values that serve as input data for the tool, allow the visualisation of temporal NDVI profiles for any or all QDSs for any or all seasons between 1992/93 and 2002/03 as shown in Figures 4.4.7 and 4.4.8.

The spreadsheet tool essentially extracts the relevant phenological milestone values from these profiles. The profiles in figure 4.5.7 show the expected vegetation response to the rainfall gradient that
increases from west to east across the country. It also shows a steady post-peak decline in NDVI values that continue right up to the start of the next growing season.

This phenomenon is not an anomaly confined to a particular year, as shown by the plots for three different seasons in figure 4.4.8. An analysis of the seasonal profiles for one QDS situated in N.E. Namibia (QDS 1718Bc) shows that the greening up and senescing cycle consists of a series of peaks and troughs with no plateaux during the wet season and no flat valley floors during the dry season (figure 4.4.9). The result is an overly long growing period and a very late “end of dry season” date as shown in figure 4.4.10 e,h,i. Post growing season peak metrics should therefore be used with caution.

Spatial representations of the results of the NDVI metrics extracted by means of the spreadsheet tool are shown in figure 4.4.10.
Figure 4.4.10  Selected metrics derived from raw NDVI data, using the spreadsheet tool. The values are arithmetic means for the 10 year period covered by this study. a) Maximum NDVI value attained during the season, b) Mean NDVI, c) Integrated NDVI for growing season, d) Length of green-up season, e) Length of senescing season, f) Month in which maximum NDVI is attained, g) Month in which the main green-up starts, h) Month in which the growing season ends, i) Length of growing season.
4.5 Burned Area Data

The utility of AVHRR data for burned area detection has been well documented (e.g. Pereira and Setzer 1996, Flasse and Ceccato 1996, Harris 1996, Barbosa et al 1999, Craig et al 2002). Burned areas in Namibia show up in all 5 channels of AVHRR data for daytime acquisitions (figure 4.5.1). A number of methods for extracting these features have been described in the literature. Examples include analysis of the linear relationship between channel 2 reflectance and the fraction of area burned (Razafimpanilo et al 1995), contextual pixel-integrated temperature evaluation using

![Figure 4.5.1 NOAA AVHRR raw channel 1,2,3 & 4 images. Burned areas in all channels show up as dark patches in pre-calibration data, as indicated by the red arrows.](image-url)
chapter 3 and 4 data (Harris 1996), applying thresholds to indices derived from channel 1 and 2 time series data (Fernandez et al 1997), rule based (CART) statistical supervised classification (Pereira et al 1998) and multi-temporal, multi-threshold analysis of indices derived from channel 2 and 3 data (Barbosa et al 1999). This study applied a multi-threshold pairwise image comparison approach to channel 3 and 4 data as developed for Namibian savanna areas by Trigg (1998) and described by le Roux (2000).

4.5.1 AVHRR data and burned area detection in Namibia

Burned area mapping in Namibia, using locally acquired NOAA AVHRR HRPT data, was pioneered by Trigg (1997) and institutionalised at the Etosha Ecological Institute by le Roux (2000). The direct reception era ended in 2004 and burned areas for Etosha National Park are currently mapped from MODIS data, while National level mapping is done by the National Remote Sensing Centre of the Directorate of Forestry in Windhoek.

As mentioned in section 1.1, AVHRR data have been used for burned area mapping for decades. No alternative optimal source of satellite data was available for the period covered by this study. As discussed in Chapter 3, there is a trade-off between spatial and temporal resolution, with other factors such as cost and effort also coming into play. For instance, there can be no doubt that Landsat TM data with its 30 m pixel size, suitable spectral range and 15 day revisit capability is potentially far superior to the 1.1 km AVHRR spatial resolution. However, in practice, obtaining an image every 15 days or even every month for many parts of Africa is not a reality for the period covered by the study. Using available imagery would result in a map covering a range of dates rather than a single date. While this is not an insurmountable problem, the cost involved proves prohibitive. No fewer than 57 Landsat scenes are required to cover Namibia for a particular date. If burned areas are mapped at monthly intervals, this amounts to 684 scenes per year, and 6840 scenes for the 10 year period of the study. The amount of work involved in processing these images makes high resolution data for national level studies even less suitable.
By contrast, the AVHRR data comes free of charge, has a suitable spectral range, greater radiometric depth, and a single image covers the entire country. The generalization of spatial features because of the moderate AVHRR pixel size does not have an adverse effect on burned area statistics derived for Namibia where burned areas are mostly quite extensive. Under these circumstances, the shapes of the mapped area is understandably different from reality (figure 4.5.2), but the areal extent measured from it is within acceptable limits (le Roux 2001).

This study uses a monthly time step for the burned area maps. In certain parts of the world, or for certain spectral ranges, this period may be too long, resulting in data loss caused by burned areas that are created and then recover to a pre-fire state within a month. This is not the case in Namibia. Burned areas in this semi-arid environment are very persistent in AVHRR data, with fire scars from the Etosha National Park remaining detectable for over a year. The spectro-temporal response of a burned area in the more mesic north east of the country (figure 4.5.5) is shown in figure 4.5.3. While the time period covered by these data only spans two months, it nevertheless illustrates the separability of a Channel 3 burned area signal over a 30 day period. The fluctuations in

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Figure 4.5.2 Comparison of a burned area mapped from Landsat ETM+ imagery (solid brown) and AVHRR (diagonal hatching).

Figure 4.5.3 Spectro-Temporal response curves of AVHRR channels 1-5 for a burned area over a 60 day period. The background response of unburned vegetation is represented by the black dotted line.
Reflectance and Brightness Temperature (BT) values that give rise to the peaks and troughs in all channels in figure 4.5.3 are caused by signal perturbations such as view angle, solar zenith angle and atmospheric effects such as water moisture and thin clouds. The general increase in BT values over time is caused by the advance of summer.

The spectral response of the five AVHRR channels across burned and unburned areas of north-eastern Namibia (figure 4.5.5) are shown in figure 4.5.4. The response in channels 1 and 2 are not useful despite the decreasing Reflectance in channel 2 across the first burned area. This is probably as a result of dark ash residue. Conversely, Reflectance across the second burned area increases, probably as a result of exposed bright soil and the absence of black ash. The responses from channels 3-5 are clear – burned areas cause a rise in BT which is particularly noticeable in channel 3.
Figure 4.5.5: NOAA AVHRR calibrated channel 1, 2, 3, 4 & 5 images. Burned areas show up as light patches in channels 3 to 5. The spatial reflectance profile in figure 4.5.3 follows the red line. The burned area temporal reflectance curves in figure 4.5.4 are from the pixels under the red square, while the background BT values for channel 3 are from the pixels under the green square.
4.5.2 Fire regime metrics

According to Trollope (1993), a Southern African savanna fire regime has four components:

- Type of fire (ground, surface, crown)
- Intensity of fire (heat energy released – see chapter 2, section 2.3)
- Season of burning (late hot-wet, early cool-dry, late hot-dry, early hot-wet)
- Frequency of burning (timing interval between fires)

Of these four components, only the last two can be reconstructed directly from Remote Sensing data with any accuracy, while the first two are usually inferred or modelled. The different effects of different fire intensities on the structure of savanna vegetation is well known, but the reliable measurement of this fire regime component from routinely available satellite imagery remains particularly challenging (Russel-Smith et al 1998).

Operational ground based measurement is even more difficult, and led Trollope (1993) to declare that “obviously it is not logistically possible to monitor the intensities of the fires that occur in the KNP annually.” For this reason, some studies (e.g. Keely et al 1999) imply fire intensity from the seasonality of burning. This enforced flexibility in selecting the parameters that need to be measured in order to define a fire regime was reviewed by Krebs et al (2010) who concluded that “today the concept of “fire regime” refers to a collection of several fire-related parameters that may be organized, assembled and used in different ways according to the needs of the users”. In order to describe the Namibian fire regimes, primary fire metrics were retrieved directly from the burned area data. Long term metrics were then derived from the time series of primary metrics, while additional metrics were obtained by combining the primary fire metrics with the phytophenological data described in section 1.4.2. Following the work of Dwyer et al (2000), the following metrics were derived from the AVHRR data for each QDS:

**Primary metrics:**

For each year individually:

*Season start:* The month in which the first burn scar appears.
Season end: The month after which no new burn scars appear.

Season peak: The month during which the most extensive burning occurs.

Derived metrics for the 10 year time series:

Average duration of fire season: The arithmetic mean of the number of months in the fire season.

Modal duration of fire season: The most commonly occurring value for the number of months in the fire season.

Average peak burn month: The arithmetic mean of the months in which the most extensive burning was recorded.

Modal peak burn month: The most commonly occurring value for the month in which the most extensive burning was recorded.

Average burn area: The arithmetic mean of the area of a particular QDS that burns, expressed as a percentage of the total QDS area.

Fire frequency: The number of fire events recorded per QDS during the study period.
Additional metrics:

*Time from peak to burn start:* The number of months between the peak of the growing season and the start of the burning season.

*Time from peak to burn end:* The number of months between the peak of the growing season and the end of the burning season.

*Time from end of senescence to burn start:* The number of months between the end of the senescence period and the start of the burning season.

*Time from end of senescence to burn end:* The number of months between the end of the senescence period and the end of the burning season.

*Time from start, to next growing season:* The number of months between the start of the burning season and the start of the next growing season.

*Time from end, to next growing season:* The number of months between the end of the burning season and the start of the next growing season.
4.5.3 Methodology

Monthly AVHRR blockfiles for the 10 year period from 1994 to 2003 were selected from the Etosha Ecological Institute’s archive. Where possible, nadir view files acquired around the middle of the month were selected, and in all cases cloud free data were used. Pre-processing was accomplished using the NOM software. Using the single channel extraction function in the NOM, it is possible to retain the original 10 bit radiometric resolution whilst producing 8 bit images. Normally, scaling data from the 1024 values in 10 bit imagery to 256 possible values in 8 bit data will result in a precision of 0.25 (1024 ÷ 256 = 4), which effectively places groups of 4 original values into one bin. However, by investigating the image histograms, it is possible to define a useful range of values to assign to the available 256 bins. Figure 4.5.6 shows a Channel 1 Reflectance image for part of north-eastern Namibia, with Botswana’s Okavango Delta in the centre of the image. Inspection of the histogram shows that only a narrow range around DN 128 is used by data, as indicated by the red and blue markers. The range of DNs between 0 and 256 corresponds to a % Reflectance range of 0 to 25% (0-100% = 0-1023). By specifying these values of 0 and 25 as respective

Figure 4.5.6  NOAA AVHRR raw channel 1image, in original 10 bit radiometric resolution. The actual data values cover a very narrow part of the available 0 – 1023 DN range.
minimum and maximum output values, the NOM produces a calibrated channel 1 image with a precision of 1, across the 0-255 range as shown in figure 4.5.7. Bare soil and other highly reflective surfaces such as the Makgadikgadi salt pan (at lower right in figure 4.5.7) with Reflectance values above the 25% upper limit are saturated. This is of no consequence to the detection of burned areas which show up as areas of lower Reflectance compared to surrounding vegetated land.

This process of raw image histogram inspection and selection of a suitable output range was applied throughout, to produce monthly calibrated channel 1,2,3 and 5 images that retained the original 10 bit radiometric resolution, and that cover the 10 year study period. All images were then reprojected from the original Satellite Projection to a Plate Carrée Projection as described in section 1.3.1 and exported as uncompressed bitmaps.
Great care needs to be taken with the geometric correction process when the detection and mapping of burned areas relies on temporal change detection. Misregistration between multi-date image pairs result in artefacts along edges of features, which are indistinguishable from true burned areas.

![Figure 4.5.8](image)

*Figure 4.5.8 A) Overview calibrated channel 3 image of north-eastern Namibia and the Okavango Delta in Botswana, showing a complex pattern of extensive burn scars. B) Detail view of a simple burn scar circled in red at lower left of the overview image. C) Two-band colour composite, showing no change in the pale yellow burned area. D) The same colour composite, now showing what appears to be new burned areas in orange.*

This problem is inherent in all multi-temporal change detection procedures, and is illustrated in figure 4.5.8. When multi-temporal AVHRR channel 3 images are displayed as colour composites with date T assigned to the green layer and date T+ assigned to the red layer, areas that have not changed between dates are displayed in yellow, while burned areas that have formed since date T are shown in red. In figure 4.5.8C, the channel 3 image shown in B is displayed as a colour composite. As expected, there are no red areas because the composite is for a single date simulation, where the
channel 3 image is assigned to the red layer and the same image assigned to green. This represents a “no new burns between dates” scenario. Figure 4.5.8D shows the same colour composite, but the registration of the red band image has been manually offset by two pixels along the X-axis. The result is what appears to be a burned area progression from left to right along the vertical edges of the burn scar. During the burned area mapping process, these areas would be combined with true changes between dates, thereby falsely increasing the area of the burns. In order to ensure sub-pixel registration, all images from all dates were geometrically corrected using a series of ground control points located on a 250 metre resolution MODIS colour composite image of Namibia (figure 4.5.9), with RMS errors of less than 1. At the same time, the projection was changed from Plate Carrée to Albers Equal Area using a first order polynomial nearest neighbour transformation that preserves original data values as described in section 3.2.

Binary images of burned/not burned areas were produced using ER Mapper® software. Multi-temporal image pairs were systematically analysed using a series of 32 frames that cover Namibia. For each mapping date, an algorithm was developed that subtracts the previous date image from the current date. This typically produces an image with relatively low values across most of the image where gradual changes are caused by seasonal biophysical changes to the land cover or external perturbations to the signal such as atmospheric conditions or view/solar angles. Savanna fires on the other hand cause major changes in surface Reflectance and Brightness Temperature and show up in the subtraction image as areas of relatively high values. Burned areas that are present in both images have values that are similar to unburned areas. Burned areas are therefore separable from the background by setting a single threshold above which all
pixels are assigned to the burned class and below which all pixels are assigned to the unburned class.

Surface Reflectance as well as Brightness Temperature values vary across the Namibian landscape and as a result, subtraction values for different parts of the country also vary geographically. This means that a threshold applied to the Caprivi region might erroneously include large areas of Kunene region that did not burn. Conversely, a threshold that is suitable for south-central Namibia might exclude many burned areas in the Kavango region. For this reason, an iterative multithreshold approach is applied to the Namibia image based on the 32 mapping frames. Where necessary, different thresholds are applied to individual burned areas within a single frame in order to reduce commission or omission errors. The resulting binary images for the 32 frames are combined into a single image and converted from raster to vector format to produce spatial distribution maps of burned
areas for each year (figure 4.5.13) The monthly burned area vector files for each year is intersected with the QDS vector file using the ArcView® 3.3 GIS software package and its Spatial Analyst™ 2.0a extension, and the fractional burn area per QDS is calculated. These values for each month for each QDS were then added to a Microsoft® Excel™ table. In this way, a spreadsheet of values with a monthly time step for a particular QDS was built up for a twelve month period. A spreadsheet tool was developed to combine the burned area data with NDVI data to extract the derived metrics described in section 1.5.2. These metrics were then appended to the QDS vector layer database file, thereby allowing the visualisation of the spatial distribution of the fire regime parameters as shown in figure 4.5.13. The workflow is illustrated in figure 4.5.11.

![Flow diagram illustrating the burned area feature extraction process.](image)

*Figure 4.5.11 A flow diagram illustrating the burned area feature extraction process.*
4.5.4 Results

A section of the spreadsheet tool that was developed to extract the burned area metrics for each of the 1300 Quarter Degree Squares is shown in figures 1.5.12. The tool combines the phytophenological metrics derived from NDVI data as described in the previous section, with the burned area data to produce fire regime metrics. As discussed in section 1.4.4, the phytophenological metrics for the post growing season peak period are susceptible to degradation caused by the gradual decrease in NDVI values throughout the dry season, rather than a discrete end to the senescence period.

This affected some initial metrics which are shown in the spreadsheet, such as Fire season starts x months after end of senescence season (figure 4.5.12, spreadsheet column T), and resulted in negative values for some squares. These values were discarded and fire regime metrics expressed in relation to the Peak of Growing Season phytophenological metric. Spatial representations of the fire regime metrics extracted by means of the spreadsheet tool are shown in figure 4.5.14.
Figure 4.5.13  Areas burned per year between 1994 and 2003.
CHAPTER 4. SATELLITE DERIVED DATASETS – VEGETATION INDICES AND BURNT AREAS

Figure 4.5.14 Selected metrics derived from phytophysical metrics and burnt area metrics, using the spreadsheet tool. The values are means or modes for the 10 year period covered by this study.

a) Quarter degree squares in which burning was recorded. b) Duration of the burning season (mode). c) Peak burn month (mode). d) Percentage of QDS affected by fire (mean). e) Burning starts after peak of growing season (mean number of months). f) Burning ends after peak of growing season (mean number of months).
4.6 Summary

Vegetation index data in the form of NDVI images, and burned area data for the Etosha National Park have been produced in Namibia from locally received NOAA AVHRR HRPT data since 1993. However, due to the institutional focus on the area where the receiving station was installed, reliable NDVI images that cover the whole country at daily time intervals remain available only as subsets of lower resolution global data sets.

GIMMS maximum value NDVI composite images with a 15 day time step were used to produce phytophenological metrics for every growing season between 1994 and 2003. This process was facilitated by the successful development of a semi-automated spreadsheet tool that extracts the relevant metrics for each of the 1300 quarter degree squares that cover the study area. Burned areas for the entire country were mapped for every year between 1994 and 2003 using a monthly time step, and fire regime metrics derived for each of the 1300 quarter degree squares using a semi-automated spreadsheet tool.

It can therefore be concluded that the first four goals of Objective 1 have been met and the first research question answered. These were:

**Objective 1:** To characterise Namibian fire regimes in the spatial and temporal domains.

Goals:

- Production of a dataset consisting of digital burned area maps for Namibia, aggregated to a monthly level and spanning a ten year period from 1994 to 2003.
- Development of an semi-automated system to extract a range of relevant metrics from this dataset.
- Production of comparable vegetation index datasets.
- Development of a semi-automated system to extract a range of relevant metrics from this dataset.

Research question: Is it possible to develop semi-automated systems that enable the characterisation of Namibian fire regimes?
CHAPTER 5. FIRE REGIMES – WHERE AND WHEN DOES IT BURN

“It is almost universally felt that when we call a country democratic we are praising it; consequently, the defenders of every kind of regime claim that it is a democracy, and fear that they might have to stop using the word if it were tied down to any one meaning.”

George Orwell - (1903 – 1950)

5 FIRE REGIMES – WHERE AND WHEN DOES IT BURN

5.1 Introduction

Typically, a fire regime describes the nature of fires that have occurred in a particular area over an extended period of time. While there is no such thing as a good or bad fire regime, the original application of the term regime to biomass burning in Africa during the early part of the 19th century most certainly had bad connotations, and applied the word in its original sense – to rule or to reign over (Krebs et al 2010), implying that the natives were imposing a reign of fire over the natural order of climatic climax forests that would devastate this valuable resource and deprive the colonising powers of an export commodity. Today the term is no longer tied down to any one meaning, and fire ecologists are free to include and exclude parameters depending on their needs.

Nevertheless, the four components (type, intensity, seasonality and frequency) that define a Southern African savanna fire regime as proposed by Trollope (1993) remain a standard for the description of local fire regimes. Of these four components, intensity and frequency have the greatest impact on the environment. Hot fires that burn the same area every year will have a much more profound effect on the vegetation than cooler fires at the same frequency, or an equally hot fire with several years between burns. As discussed in chapter 2 (section 2.3), seasonality is one of the most important determinants of fire intensity and for the purposes of this study the two terms seasonality and intensity will be combined into one term – fire severity – as defined in section 2.3 (figure 2.3.1).

This chapter will therefore describe and discuss fire regimes in Namibia in terms of:

- Type
- Severity
- Frequency
5.2 Regime components

**Type of fire** refers to the level at which combustion and fire propagation occurs. Three categories can be distinguished: ground fires, surface fires and crown fires. Ground fires burn decomposed organic plant material below the ground surface through an oxygen deficient smouldering combustion process. Surface fires burn plant material such as grasses, shrubs, leaf litter and fallen branches at ground level. Lower branches of trees may be scorched, but the crowns remain unaffected. Crown fires are usually ignited by surface fires, after which they often burn ahead of the surface fires by propagating across the tree canopy.

**Severity of fire** refers to the loss of, or damage to organic matter caused by the fire. Fire severity is a qualitative indicator of the immediate effect of a fire and should not be confused with post-fire ecosystem response. Severity was discussed in detail in chapter 2.

**Frequency of a fire** refers to the number of fire events that occur in a particular area per unit time. It is sometimes used interchangeably with fire interval or fire return period, although these refer to the time between successive fires in a particular area.

5.2.1 Type

The predominant type of fires that occur in Namibia can be classified as surface fires. Ground fires that burn in peat deposits over extended periods of time occur in small parts of the Caprivi region, while crown fires are almost unheard of.

5.2.2 Severity

Fire severity is largely determined by fire intensity, which in turn is a function of three factors: amount of fuel consumed, heat yield of the fuel and rate of spread of the fire. Fuel availability or fuel load is a good indicator of fuel consumed and is the most important determinant of fire intensity, raising the fire intensity by a factor of six with every doubling of the available fuel load. As mentioned in chapter 4, seasonal integrated NDVI values can be used to derive plant biomass production estimates for
that particular season. Although it is possible to convert these NDVI values to more understandable units such as kg/ha, the disaggregation of this figure into evergreen biomass which contributes little to the fuel load and rain-green vegetation which makes up the bulk of combustible material, is beyond the scope of this study. For this reason, raw NDVI values are used throughout, to derive a relative indication of the potential fuel loads.

Figure 5.2.1 Mean seasonal integrated NDVI values, with isohyets at 50 mm rainfall intervals.

The sum of the NDVI values under the growing season curve is presented in figure 5.2.1. As is to be expected, the values follow the rainfall gradient with the highest values occurring in the north-eastern parts of the country where the mean annual rainfall exceeds 500 mm. If all other parameters remain equal, these higher biomass production/potential fuel loads will cause fires in the north-east to have a much higher intensity than those in the south or west of Namibia.
The rate of spread of the fire is affected by a number of factors as discussed in chapter 2. The most important factor is the actual wind speed during the fire. Data recorded at climatic weather stations across the country show that for all inland stations, except Katima Mulilo, wind speeds increase during the late dry season months of September, October and November, as shown in table 5-1.

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Table 5-1. Mean daily wind speeds recorded per month at weather stations across Namibia, in metres per second.

Increasing wind speeds from 0 to 3.6 m/s increases the rate of spread of headfires exponentially, which in turn increases the intensity of the fire by increasing oxygen supply and accelerating the pre-heating phase. The spatial distribution of these stations and mean daily wind speeds for each month is shown in figure 5.2.2. Fires in areas with the same fuel loads, but which occur later in the year, will have a much higher intensity than those which occur during the winter months when wind speeds are lower.
The seasonality of the fire regime in Namibia, as indicated by the median month during which the largest proportion of a QDSs is affected by burning, is shown in figure 5.2.3. Most (72.8%) of the fire affected area (FAA) burns during the late dry season months of August to September. These fires predominate in the north-eastern regions of Omaheke, Kavango and Caprivi. Early burning during the cold winter months of June and July is experienced in only 11.5% of the FAA, while the remaining 15.6% of the area burns during October.

Heat yield of savanna grassland fuels is a constant, as discussed in chapter 2. It can therefore be concluded that fire intensity, and therefore fire severity, will be greatest where burning occurs later in the year in areas with higher fuel loads. The severity of fires and the subsequent effect on the ecosystem can be mitigated by reducing the fuel load or by burning during the time of the year when wind speeds are lower.
Almost half of the FAA (48.4%) has a very short burning season with a median duration of only one month. Along the Okavango River and across the Caprivi strip into Eastern Caprivi, the season extends over a much longer period of up to six months. The remaining 33% of the FAA has a season of intermediate duration lasting from two to three months.

From figures 1.2.3 and 1.2.4 it is clear that although the north-eastern part of the country burns mainly during August and September, the actual burning season in this area extends over a period of six months. Some burning therefore occurs relatively soon after the end of the growing season when fuel moisture levels are still high. This would further reduce fire intensity, thereby limiting the impact of the fires on woody vegetation in particular.
Fires that occur at the start of the season are often referred to as early burns while those that occur during the end of the season are called late burns. In this somewhat back to front way, the season is defined by the fires, rather than defining the season and then classifying the fires accordingly. Alternatively, the season is defined by arbitrary groupings of calendar months based on meteorological data, so that Namibian fires that occur between April and June are early burns, those between July and August are mid season burns and the September to November fires are late season burns. While this approach takes general climatological parameters such as temperature into account, it discounts the temporal and spatial variability of the rainfall that drives the fuel production. This variability, as indicated by the peak in NDVI values recorded per QDS, is shown in figure 5.2.5. The only clear pattern that emerges, is that the growing season peaks several months later in the west than in the eastern parts of the country. While April fires in the west would therefore clearly be early burns, April fires in the east would already be mid or late season burns since they occur two to three months after the peak of the growing season. For this reason, the timing of burns will be defined in relation to the peak of the growing season per QDS.

Figure 5.2.5 Growing season peaks per Quarter Degree Square. There is a general progression from east to west across the country.
The start of season time lag, calculated as the average number of months from the peak of the growing season to the start of the burning season, is shown in figure 5.2.6. Almost half of the area (49.5%) starts burning four to six months after the start of the senescence phase. These areas are widely separated geographically, and occur in the semi-arid north-west, the arid central western parts, as well as in the more humid north-eastern regions of Omaheke and Kavango. A shorter lag of between 2 and 4 months applies to 31.3% of the FAA, with a similar geographic distribution as the aforementioned class, while only 7.7% of the area starts burning almost as soon as photosynthetic activity starts decreasing. This area is confined to the wettest parts of the country, along the Caprivi strip and into East Caprivi. The greatest lag of between 6 and 8 months applies to 11.1% of the FAA, and occurs mainly along the Omaheke/Otjozondjupa regional borders near the town of Otjinene and Epukiro Post 3.
CHAPTER 5. FIRE REGIMES – WHERE AND WHEN DOES IT BURN

The end of season time lag, calculated as the average number of months from the end of the burning season to the start of the next growing season, is shown in figure 5.2.7. More than half of the FAA (57.6%) stops burning between 2 and 4 months before the start of the next growing season. In northern Kavango region, as well as part of Omaheke region east of Epukiro post 3 and along the Omaheke/Otjozondjupa boundary east of Okondjatu, the fire season extends right up to the start of the next growing season. This 0–2 month class is relatively small at 17.3% of the FAA, and is an indication of the insignificance of lightning induced fires as a potential cause of fires in Namibia: 82.7% of the FAA stops burning more than two months before the start of the next thunderstorm driven greening up season. Scattered patches of FAA (21.7%) stop burning 4-6 months before the start of the next growing season, while a very small percentage (3.4%) of the area stops burning 6-8 months before the next season.

Figure 5.2.7 The average lag between the end of the fire season and the start of the next growing season.
5.2.3 Frequency of fire

Despite its seemingly straightforward definition – a simple count of the number of fire events that occur in a particular area per unit time – fire frequency remains one of the most misreported and complex parameters in the fire regime suite. Frequency of burning, combined with fire intensity, can have a profound effect on both structural and floristic composition of the fire affected vegetation. Regular and frequent hot fires create a trap from which fire sensitive tree seedlings cannot escape. This effectively prevents recruitment and causes a skewed age distribution in the tree population. The situation can only be remedied by breaking the fire cycle or by reducing the intensity of the fires. In order to do this, accurate data is required on the fire frequency in a particular area. It is often said that large parts of north-eastern Namibia burn every second year. More often than not, what is actually meant is “burned 5 times in 10 years”. The difference is illustrated in table 5-3 where 3 burn scenarios, each with a frequency of 5 are presented. Other combinations are possible, and the impact of each scenario will vary between habitats, but the effects of the 3 scenarios on any particular area are likely to be very different. In order to reduce this ambiguity, fire frequency is substituted with fire return period (FRP), expressed as the mean number of years between successive fires in a particular QDS. The fire return periods for Namibia are shown in figure 5.2.8.

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<td>2001</td>
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<td>2002</td>
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<tr>
<td>2003</td>
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<td></td>
</tr>
</tbody>
</table>

*Table 5-2. Hypothetical fire frequency table for the same area under 3 burn scenarios, each with a frequency of 5.*

There is an east-west fire return period gradient across Namibia, with the shortest fire return periods being recorded in the north-eastern parts of the country where fires occur every year in the Caprivi and over much of the Kavango regions. The Zambezi floodplain which forms the eastern tip of the Caprivi region burns less frequently, as do parts of southern Kavango, north-eastern Otjozondjupa as well as the eastern parts of Ohangwena and Oshikoto regions. Further south and west, the return periods become longer and the pattern disappears, with relatively short return period QDSs surrounded
by areas that burn much less frequently. A notable anomaly is formed by the Etosha National Park in north-western Namibia, where park rangers implement a fire management policy that results in a fire return period that is distinctly different from that of the communal and freehold land that borders the park.

Fires are recorded annually in 17% of the QDSs that are affected by fire. **Burned areas do not necessarily cover an entire QDS, and it would therefore be inaccurate to say that 17% of the area burns every year.** With the exception of one QDS in Otjozondjupa region northwest of Tsumkwe, this class is almost entirely confined to the Kavango and Caprivi regions. It covers more than 70% of the area of these two regions. A further 17.2% of the fire affected QDSs have a fire return period of between 1 and 2 years, while 14.2% of the fire affected QDSs have a fire return period of between 2 and 4 years. 18.4% of the FAA has a fire return period of 5 years, while the remaining 33% burns very infrequently, with a fire return period of 10 years.
A relatively small fraction of any given QDS is actually affected by fire, as shown in figure 5.2.9. Only one QDS recorded a mean burn fraction of between 75 and 100 percent (actual = 91.2%). Over most of the FAA (83%), the mean burn fraction is less than 25% of a QDS. Larger fires that burn a greater percentage of a QDS occur in the north-eastern parts of the country, but even here in the Kavango and Caprivi regions, the burn fraction is only between 25 and 50 percent. The other large group in this class lies within the Etosha National Park, where a “block burning” fire management strategy is implemented. Within these two regions, smaller areas with a burn fraction of between 50 and 75 percent occur. The effect of these relatively low burn fractions throughout the FAA, is to mitigate the results of the FRP as shown in figure 5.2.8. Although 70% of the QDSs in Kavango and Caprivi record a fire every year, these fires usually affect less than half of any given QDS. The remaining 50% of the QDS may have a much longer FRP, with important implications for tree seedling survival and biodiversity.
5.3 Namibian Fire Regimes

Using the results from the previous sections, it is possible to derive fire regimes for any area in Namibia. For the purpose of this study, fire regimes are classified in terms of their expected or potential impact on the environment, based on the timing of the burning, the time lag since the peak of the growing season, the duration of the fire season, the extent of the burning, the amount of biomass produced during the growing season, and the fire return period.

Weighted values were assigned to data ranges based on the ability of the respective parameter to influence the potential impact of the fire, as shown in table 5-3. Parameters were ranked in descending order of importance:

1. Biomass
2. Timing, Time lag, FRP
3. Duration and Extent

As discussed in previous chapters, available fuel load in the form of combustible biomass is by far the most important factor in determining fire intensity and subsequent impact. The duration of the fire season and extent of burning are ancillary parameters that serve to mitigate the impact of the other parameters.
There is a clear southwest-northeast progression of fire severity that follows on from patterns observed in descriptions of the individual parameters in section 1.2. More than half of the fire affected area (53%) has a very mild to mild fire regime, mainly as a result of low biomass production and consequently low fuel loads, but also because of the long fire return period. There are exceptions within this area, with clusters of QDSs in the moderate to severe classes. This is primarily as a result of the very late burning that occurs in these parts, which cannot be mitigated by the relatively low biomass production. Severe to very severe fire regimes are almost entirely confined to the Kavango and Caprivi regions. These are areas with a long burning season, very high biomass production, very short fire return periods and extensive burning. The severe class covers 19.8% of the FAA, while only 6.3% of the FAA is covered by the very severe class.
5.4 Fire regime trends

The trend in the extent of burning, calculated from the increase or decrease in the area burned per year per QDS is shown in figure 5.4.1.

There is an upward trend over most of the FAA, with 41.7% of the QDSs showing an increase in burned area. This area is more or less confined to the north-eastern parts of the country. A few clustered areas covering 24.3% of the FAA shows downward trend in burned area, while the extent of burning is static in much of the central part of the country where no changes have occurred in 33.2% of the FAA.
The trends in burned area and other fire regime parameters cannot be explained by climatic events and fuel production alone. As can be seen from figure 5.4.2, much of the red area in figure 5.4.1 that shows an increase in burned area occurs in areas that have a decreasing trend in biomass production. Conversely, some areas that have a decreasing trend in burned area have an increasing trend in biomass production.

Figure 5.4.2  Trends in integrated NDVI values for the growing season
The trend in the month during which most burning occurs, calculated from the increase or decrease in the peak month per year per QDS is shown in figure 5.4.3. There is an upward trend in 34.9% of FAA, which indicates that most of the burning in these QDSs now occurs later in the season. This is likely to increase fire intensity and impact. 25.1% of the area shows a trend towards earlier burning, while the trend is static over the remaining 40% of the fire affected area.

The early burning trend could be attributed to a successful project by the Non-Governmental conservation organisation – IRDNC\(^1\) to involve local communities in early burning practices. Their pilot area in east Caprivi is indicated by the arrow in figure 5.4.3.

\(^1\) Integrated Rural Development & Nature Conservation

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**Figure 5.4.3  Trends in the month during which most burning occurs.**
The trends in the duration of the burning season are shown in figure 5.4.4. There is no change over most of the FAA (56.6%). QDSs that exhibit this static trend correspond closely to QDSs that have a burning season duration of only one month (figure 5.2.4) and a long FRP (figure 5.2.8). In other words, areas that are not fire prone have remained so. A decreasing trend is observed in 22.5% of the QDSs in the fire affected area, while the remaining 20.9% of the FAA shows a trend towards a longer duration in the burning season. The arrow in figure 5.4.4 again indicates the IRDNC pilot area, which shows an increase in fire season duration over a small part of one QDS, while adjacent QDSs show a decreasing trend. This can be ascribed to the fact that successful early burning reduces the fuel load sufficiently to preclude further fires later in the year. This is supported by figure 5.4.1 which shows an increasing trend in the extent of the burned area for these QDSs, despite the downward trend in biomass production as illustrated in figure 5.4.2.
5.5 Summary

Sixty two percent of the Quarter Degree Squares (QDSs) in Namibia were not affected by fire during the 10 year study period from 1994 - 2003. These areas are confined to the arid southern and western parts of the country. Fire affected areas occur across the central, northern and eastern parts of the country, where most of the burning takes place during August and September (figures 5.5.1 below and 5.2.3 p75). A small proportion of this area starts burning within a month or two after the peak of the growing season, but over much of the area the lag is between 4 and 6 months (figures 5.5.2 below and 5.2.6 p78).

For just over half of the QDSs, the burning season extends over a 2 - 6 month period, while the remaining 48% have a very short season of only one month (figures 5.5.3 below and 5.2.4 p76). The burning season continues into the start of the next growing season in only 17% of the fire affected QDSs (figures 5.5.4 below and 5.2.7 p79).

Figure 5.5.1  The proportion of QDSs with different fire season peaks.

Figure 5.5.2  The proportion of QDSs with different lags between the start of the senescence period and start of the burning season.

Figure 5.5.3  The proportion of QDSs with different fire season durations.

Figure 5.5.4  The proportion of QDSs with different lags between the end of the fire season and the start of the next growing season.
More than half of the QDSs in the FAA have a fire regime that can be described as very mild to mild, largely as a result of their geographic position in the drier western and southern parts of the country, with low biomass production from low rainfall. Only six percent of the FAA has a very severe fire regime (figures 5.5.5 below and 5.3.1 p84).

No QDSs burned entirely. Only one QDS was affected over more than 75% of its area with a burn fraction of 91.2%. The vast majority of squares were affected over less than 25% of their surface area.

This chapter presents the results of combining spatio-temporal phytophenological metrics with burned area metrics to produce spatially explicit datasets which characterise Namibian fire regimes, thereby achieving the final goal of Objective 1. This achievement, in conjunction with those of the previous chapter, therefore also concludes the answering of research question for Objective 1. This question was: Is it possible to develop semi-automated systems that enable the characterisation of Namibian fire regimes.
“The first man who, having fenced in a piece of land, said “This is mine”, and found people naïve enough to believe him, that man was the true founder of civil society.”

Jean Jacques Rousseau (1712-1778) - Discourse on the Origin and Basis of Inequality Among Men (1754)

6 LAND USE – A QUESTION OF CHOICE?

6.1 Introduction

A meaningful description of land use is not possible without a clear definition of the term, since many classifications erroneously use it interchangeably with land cover, or mix land cover types and land use classes. For the purpose of this thesis, the definition of land use is adapted from that of Di Gregorio and Jansen (1998):

Land use is the arrangement, activity and or input by people to produce, change, maintain or use a certain land cover type.

The way in which a particular piece of land can be used is defined not only by its biophysical characteristics, but often also by indirect factors such as ownership and control. People who do not own the land are restricted in what they may do on it by those who are in control. In Namibia, 56% of the land remains the property of Central Government, while 43% is privately owned by individuals or companies. The remaining 1% belongs to Local Authorities as shown in figure 6.1.1.

Figure 6.1.1 Land ownership. The grey areas that belong to Local Authorities are urban areas. (Adapted from Mendelsohn et al, 2002)
6.2 Authority over the land

The control over farm land under private ownership lies with the individual or company that owns the land. This land is designated as freehold and may be bought and sold. On Government owned land that is designated as communal, the control over the land lies with Regional Authorities who control access to land through their Traditional Authorities. While communal farmers have control over their individual farmlands, they do not own the land and are not able to buy or sell the land on which they reside. Communal areas that are not allocated are intended to be available to all as a shared resource. The different land designations and who they are controlled by are shown in figure 6.2.1.
CHAPTER 6. LAND USE – A QUESTION OF CHOICE?

Figure 6.2.2 Land use. (Adapted from Mendelsohn et al, 2002).
6.3 Land Use

There are eight distinct land use types/classes in Namibia, as described by Mendelsohn et al (2002). These are:

1. Agriculture and tourism on freehold land
2. Large scale agriculture on communal land
3. Small scale agriculture on communal land
4. Government agriculture
5. Resettlement
6. State protected areas
7. Urban
8. Other government or parastatal

6.3.1 Agriculture and tourism on freehold land

This land use type covers 43.3% of the country as shown in figure 6.3.1, and involves what in Namibia is referred to as the “commercial farms”. These farms are discrete parcels of freehold land, owned by an individual who holds deed and title. Agricultural activities are mainly centred on cattle and or sheep farming for meat production. The farm is run as a commercial enterprise with significant input and investment from the farmer in terms of infrastructure and breeding stock. The main source of revenue is generated from the marketing of livestock, although many farmers have added tourism based enterprises such as wildlife safari lodges and trophy hunting.
6.3.2 Large scale agriculture on communal land

This land use type covers 5.9% of the country (figure 6.3.2) and involves animal husbandry on allocated as well as appropriated farms similar to those on freehold land. While some of these farms are meant to be run as commercial enterprises, many large ranches have been appropriated and fenced off illegally by relatively wealthy individuals to serve as investments. This practice runs against the spirit of communal land use, and deprives relatively poor individuals from access to reserve grazing and other resources.

6.3.3 Small scale agriculture on communal land

This land use class covers 30.4% of the country (figure 6.3.3) and mainly involves open access animal husbandry on communal land, supplemented by subsistence agriculture on very small parcels of land allocated to individuals by the traditional authorities. Little or no infrastructure development is required, and the input and investment by the farmer is very small compared to those of the farmers on freehold land. As a result, the yields are low and in some years many farmers in communal areas are in need of food aid.

6.3.4 Government agriculture

This land use class covers 0.7% of the country (figure 6.3.4) and consists of livestock quarantine camps that cover large areas along the foot and mouth disease cordon fence (red line in figure 6.3.4), and so-called experimental farms dotted around the country.
6.3.5 Resettlement

This land use class covers 0.8% of the country (figure 6.3.5) and consists mainly of “commercial farms” acquired by Government before and after independence. In an attempt to accommodate as many people as possible in the resettlement scheme, each resettlement farm that was previously owned by a single individual, was sub-divided into smaller portions. Each portion was then allocated to a resettled family who is expected to farm “commercially” on it.

6.3.6 State protected areas

This land use class covers 14.1% of the country (figure 6.3.6) and consists of areas designated as national parks, game reserves and recreation areas.

6.3.7 Urban

Urban land use covers 0.9% of the country as shown in figure 6.3.7, and is comprised of built up areas in towns and cities, as well as the undeveloped town lands that surround them.
6.3.8 Other government or parastatal

This land use type covers 3.9% of the country and consists mainly of a large block of land in the southern Namib desert known as Diamond Area 1 or the Sperrgebiet. This area has been added to the protected area network of parks and game reserves and awaits proclamation as such. Many of the other areas scattered around the country are state owned land without a specific use.

6.4 Summary

All land in Namibia is owned either by the Government, or privately by individuals or companies. Private land owners are generally at liberty to decide how they are going to use the land and what physical changes they are going to make to the landscape. Occupants of communal areas on the other hand, require permission from various authorities for most land use related activities, such as when they need to establish a new field or want to relocate their homestead.

There are eight land use classes in Namibia, with the largest class involving agriculture on freehold land. Together with the second largest class which involves agriculture on communal land, these two classes account for 73.7% of the country’s area. This makes agriculture the most common land use, involving the majority of the population.

The land use classes as discussed in this chapter are necessarily broad. Several subdivisions are possible within any of the classes such as cattle farming, or sheep farming for mutton or for karakul pelts.

Even within these subdivisions, the key issue in terms of the effect that land use has on the spatio-temporal characteristics of savanna fires, is how land management is applied to a particular landscape within any given land use class or subdivision.

Figure 6.3.8 Spatial distribution of land use class 8 – Other government or parastatal.
(Adapted from Mendelsohn et al, 2002)
CHAPTER 7. RELATIONSHIPS – IS THERE A DIFFERENCE?

"The thinker makes a great mistake when he asks after cause and effect - they both together make up the indivisible phenomenon."

Johann Wolfgang von Goethe (1749 – 1832)

7 RELATIONSHIPS – IS THERE A DIFFERENCE?

7.1 Introduction

When conducting experimental research, it is possible to control one variable while measuring the response of another. Performing regression analysis on the results allows the investigator not only to determine the extent to which one variable is affected by the other, but to predict how one will behave if the value of the other is increased or decreased. Under such circumstances, it can be said that the variation in Y is caused by a corresponding variation in X. In this study however, the investigator had no control over any of the variables that were measured. It is therefore not possible to establish causal relationships. In many instances these would be nonsensical anyway - a null hypothesis that states that low livestock numbers cause extensive burning would not make sense. Instead, we expect that high livestock numbers will have the effect of reducing the fuel load on which fires depend, thereby acting as a fire retardant. Where stocking rates are low, the fuel load might be less disturbed, thereby allowing unhindered combustion and fire propagation. Livestock numbers are but one factor that influences the available fuel load. Rainfall and land use are examples of two other influencing factors. These complex relationships are illustrated in figure 7.1.

The term “drivers of biomass burning" is currently quite fashionable. However, by focusing on what “drives" fires in African savannas, the investigation runs the risk of ignoring what might well be the main cause of extensive burning in rural areas - the absence of inhibitors. For instance, if a fire is left to burn until it runs out of fuel or runs into a barrier such as a river or road, it is not so much being driven as being ignored. In this case, the presence of so-called drivers is less important than the absence of a reason to inhibit fires. This study therefore aims to uncover both promotional as well as inhibiting factors that play a role in the relationship between fire parameters and the variables that are influenced by land use and climate.
7.2 Areas that do not burn

No burned areas were detected in the southern and western parts of the country during the ten year study period, as shown in figure 7.2.1. Based on this data, 68% of the country could be labelled as not fire prone. On the whole, the absence of fires in these areas can be ascribed to unfavourable climatic conditions. Rainfall is generally too low and or too erratic for a continuous fuel bed to develop. Even in areas where biomass production is high enough to produce sufficient fuel, the bare soil between grass tufts as shown in figure 7.2.2, prove to be a major barrier to fire propagation across the landscape.

Unburned QDSs within the FAA such as those indicated by the green arrows in figure 7.2.1 are not as easily explained by low rainfall. However, a discussion of areas that did not burn is considered beyond the scope of the present study which deals with the effect of land use on areas that did burn.
7.3 Correlation analysis

Associations between primary fire regime metrics and external variables such as human population density and landscape fragmentation, as well as environmental variables such as rainfall and biomass production were explored using nonparametric statistical methods to derive correlation coefficients for paired observations. Unlike regression analysis where the aim is to determine the dependence of variable \( Y \) on the manipulated (independent) variable \( X \), the purpose of correlation analysis is to measure the intensity of association observed between any pair of variables and to test whether it is greater than could be expected by chance alone (Sokal and Rohlf 1995). Proper calculation of the correlation coefficient relies on data that is bivariate normally distributed. For such data, Zar (1996) states that a simple linear correlation coefficient* \( r \) is commonly calculated for variables \( x \) and \( y \) as

\[
r = \frac{\sum xy}{\sqrt{\left(\sum x^2 \sum y^2\right)}}
\]

* Also referred to as the Pearson product-moment correlation coefficient (ppmcc).

which may be computed as

\[
r = \frac{\sum XY - \frac{\sum X \sum Y}{n}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{n}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{n}\right)}}
\]

However, several of the variables that are being evaluated in this study were only measured on an ordinal scale and are therefore not suitable for use with the above equation. In order to overcome this limitation, correlation analysis was performed by calculating the Spearman rank correlation coefficient \( r_s \). By converting each ordinal...
value to its rank equivalent, and because the sum of \( n \) ranks is \( n(n + 1)/2 \), equation 7-2 can be rewritten for rank correlation as

\[
rs = \frac{\sum_{i=1}^{n} (\text{rank of } x_i)(\text{rank of } y_i) - \frac{n(n + 1)^2}{4}}{\sqrt{\left(\sum_{i=1}^{n} (\text{rank of } x_i) - \frac{n(n + 1)^2}{4}\right)\left(\sum_{i=1}^{n} (\text{rank of } y_i) - \frac{n(n + 1)^2}{4}\right)}}
\]

Equation 7-3

This equation is can be simplified to the following computation

\[
rs = 1 - \frac{6\sum d_i^2}{n^3 - n}
\]

Equation 7-4

Where:

- \( r_s \) is Spearman’s rank order correlation coefficient
- \( d \) is the difference between ranks for the two observations within a pair
- \( n \) represents the total number of data pairs

### 7.3.1 Fire regime metrics and land use/climatic variables

For the purpose of the correlation analysis, fire return period, fire season duration, peak month for the fire season, and area burned was paired with human population density, livestock density, landscape fragmentation, bush density, rainfall, maximum NDVI value, mean NDVI value, NDVI greening up rate, peak month of NDVI, and sum of NDVI values. The calculations were performed using the Statsoft Statistica 6.0 software package.

ArcView 3.3 and the Spatial Analyst extension were used to extract population density figures from digital data gridded at 1 km available from the Atlas of Namibia (Mendelsohn et al. 2002). Population density is expressed as the mean number of people per QDS.
Similarly, livestock density figures were produced by converting gridded values for cattle, sheep and goats obtained from the Atlas of Namibia (Mendelsohn et al 2002) to live weight per hectare and then summing the results per species. This summed figure was then used to produce a total live weight per QDS.

Landscape fragmentation was calculated using the Calculate Feature Density (FeatureDensity.avx) extension for ArcView 3.x developed by Tim Schaub of CommEn Space (www.CommEnSpace.org). Point densities were calculated as the number of points per QDS. Line densities were calculated as the line length per QDS and polygon densities were calculated as the polygon area per QDS. These figures were summed to provide a simple indication of the total density of manmade structures within each QDS. The assumption being that a landscape with a large number of towns, villages, boreholes and other point features is more likely to be fragmented by human induced land use activities than a landscape with few or none of these point features. Similarly, line features representing roads, tracks, cut-lines and railway lines fragment the landscape by creating physical separations between land parcels. Polygons representing farm fences and their associated perimeter tracks have the same effect.

Bush density figures were extracted from gridded values of the number of bushes per hectare obtained from the Atlas of Namibia (Mendelsohn et al 2002) digital dataset, using ArcView 3.3 software and Spatial Analyst.

Rainfall values were obtained by gridding the ranked rainfall polygon data from the Atlas of Namibia (Mendelsohn et al 2002) digital dataset. The resulting grids were then reclassed in reverse order to compensate for the automated ranking procedure of the statistical software.

7.4 Relationships across land use types

A total of 455 QDSs were selected for correlation analysis across all eight land use types. The QDSs constitute the “hidden” nominal variable that ties the paired values together. The resulting correlation coefficients are shown in table 7-1.
Table 7.1 Spearman's rho values for the FAA. Correlations shown in bold red are significant at $p < .05$.

According to Sokal and Rohlf (1995), the establishment of a correlation does not give any indication as to which of the models from figure 7.1.1 are applicable to a given pair of variables. Nevertheless, they state that “perhaps the only correlations properly called nonsense or illusionary are those assumed by popular belief or scientific intuition that, when tested by proper statistical methodology using adequate sample sizes, are found to be not significant”.

Furthermore, statistical significance which is a measure of the probability that the correlation could occur by chance, should not be confused with practical significance. For instance, the fact that the correlation between FRP and Population Density in table 7-1 is statistically significant does not mean that the relationship is important. In fact, given the value of the correlation coefficient (.095) and the very large sample size (445), it simply means that the correlation is real. In practical terms it is probably not an important relationship at all. A simple way of evaluating the relative importance of correlations is by squaring the coefficient to obtain a correlation index (Zar 1996). Multiplying this index value by 100 yields a figure that shows the percentage of shared variability between the two variables (Katz 2006). For instance, a correlation coefficient of 0.99 indicates that 98.01% of the variability is shared ($0.99 * 0.99 * 100 = 98.01$), or that 98.01 of the rank values in variable A co-vary with the rank values in variable B. Similarly, and despite its apparently high value, a correlation coefficient of 0.6 means that only 36% of the variability is shared. As a rule of thumb and irrespective of sign, $r$ values between 0 and 0.1 indicate a nonexistent or very weak relationship; values
between 0.1 and 0.3 indicate a weak relationship; values between 0.3 and 0.5 indicate a moderately strong relationship, and values between 0.5 and 1.0 indicate a strong relationship. With this in mind, the correlations as indicated in table 7-1 are discussed for each of the primary fire regime metrics.

7.4.1 Fire return period

Converted correlation coefficient values, showing the percentage of shared variability between variables are shown in table 7-2. The fire return period is significantly correlated with all of the land use/climatic variables. There is a very weak negative correlation between FRP and population density, $r_s = -0.095(453), p < .05$ as well as a very weak positive correlation between FRP and livestock density, $r_s = 0.099(453), p < .05$. It would therefore seem that in some instances, a shortening of the time interval between fires is associated with an increase in human population. At the same time, an increase in the interval between fires is associated with an increase in livestock density. Weak as this association might be, it supports the commonly held belief that more people equals more matches to light fires. Similarly, the grazing impact of livestock is expected to reduce the available fuel load, thereby contributing towards a longer time required for the establishment of a combustible fuel bed. The weakness of the correlation points to the probability that this relationship does not apply to, or is very weak across many of the land use classes.

<table>
<thead>
<tr>
<th>Variability shared with Fire Return Period (%)</th>
<th>Population density</th>
<th>Livestock density</th>
<th>Landscape fragmentation</th>
<th>Bush density</th>
<th>Rainfall</th>
<th>Max NDVI</th>
<th>Mean NDVI</th>
<th>NDVI Green-up</th>
<th>NDVI total</th>
<th>NDVI peak</th>
</tr>
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<tbody>
<tr>
<td>0.90</td>
<td>0.98</td>
<td>22.6</td>
<td>24.2</td>
<td>48.3</td>
<td>37.7</td>
<td>40.1</td>
<td>4.5</td>
<td>40.8</td>
<td>9.5</td>
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</table>

Table 7-2 Converted correlation coefficient values, showing the percentage shared variability between the Fire Return Period and the Land Use/Environmental variables. Note that the numbers represent shared variability between pairs, e.g. FRP and Rainfall, FRP and Max NDVI, FRP and Bush Density etc. It does not account for the contribution of other variables, and therefore the % variability row will not sum to 100.
There is a moderately strong positive relationship between FRP and landscape fragmentation, $r_s = 0.475(453), p < .05$. In other words, across a relatively large proportion of the FAA, an increase in landscape fragmentation is associated with a lengthening of the period between burns. This seems to support the observation that roads, farm fence lines and their associated perimeter fences, as well as railway lines and towns are all fire breaks to a certain extent, that serve to inhibit the spread of fire across the landscape.

There is a moderately strong positive correlation between the FRP and bush density, $r_s = 0.492(453), p < .05$. Across large parts of central Namibia, bush thickets are associated with decreased agricultural production because the dense woody cover inhibits grass growth. This low grass fuel production would therefore require a longer accumulation period before it is able to sustain a significant fire. An increase in bush density is therefore associated with an increase in the time period between fires.

As is to be expected, there are strong negative correlations between the FRP and rainfall, maximum NDVI, mean NDVI and total NDVI, $r_s = -0.695$, -0.614, -0.633, and -0.639 respectively, (n=453), $p < .05$. The relationship between rainfall and NDVI values has been established by numerous other studies (e.g. Nicholson and Farrar 1994, du Plessis 1999, Karabulut 2003, Anyamba and Tucker 2005). Their correlation with FRP show that for a large part of the FAA, an increase in any of these variables - rainfall, maximum NDVI, mean NDVI or total NDVI - is associated with a decrease in the interval between fires. In other words, areas with high rainfall and associated high biomass/fuel production as indicated by NDVI values, burn relatively frequently.

The correlation between FRP and the vegetation green-up rate is negative and weak, $r_s = -0.211(453), p < .05$. This indicates that for a relatively small part of the FAA, an increase in the greenup rate is associated with a decrease in the fire return period. High rainfall areas in Namibia typically have extended rainy seasons, with correspondingly long green-up periods. This finding can therefore be explained by the fact that high rainfall gives rise to high biomass production, and high biomass production is positively correlated with short fire return periods.
There is a moderately strong positive correlation between the FRP and the peak NDVI month, $r_s = -0.309(453)$, $p < .05$. It could therefore be said that in some parts of the FAA, an increase in the fire interval is associated with a growing season that reaches its peak relatively late in the season. As was shown in figure 5.2.5 (p77), there is a general progression in growing season peak from east to west across Namibia. This is associated with an east-west rainfall gradient which results in lower biomass production in the west (see figure 5.2.1, p73), and therefore requires a longer fuel build-up period between fires.

### 7.4.2 Fire season duration

Converted correlation coefficient values, showing the percentage of shared variability between variables are shown in table 7-3. The fire season duration is significantly correlated with all of the land use/climatic variables. There is a weak positive relationship between Fire Season Duration (FSD) and population density, and an equally weak but negative correlation between FSD and livestock numbers, $r_s = 0.109(453)$, $p < .05$ and $r_s = -0.106(453)$, $p < .05$ respectively. Therefore, for a small part of the FAA, an increase in the duration of the fire season is associated with an increase in the human population, while an increase in livestock numbers is associated with a decrease in the duration of the fire season. This relationship is similar to the one described for the FRP, where more people mean more ignition sources throughout the season, while more cattle mean less available grass fuel to burn and therefore a shorter burning season.

<table>
<thead>
<tr>
<th>Variability shared with Fire Season Duration (%)</th>
<th>1.2</th>
<th>1.1</th>
<th>9.4</th>
<th>22.3</th>
<th>23.0</th>
<th>21.8</th>
<th>23.9</th>
<th>3.8</th>
<th>24.5</th>
<th>3.9</th>
</tr>
</thead>
</table>

Table 7-3: Converted correlation coefficient values, showing the percentage shared variability between the Fire Season Duration (FSD) and the Land Use/Environmental variables. Note that the numbers represent shared variability between pairs, e.g. FSD and Rainfall, FSD and Max NDVI, FSD and Bush Density etc. It does not account for the contribution of other variables, and therefore the % variability row will not sum to 100.
There is a moderately strong negative relationship between FSD and landscape fragmentation, $r_s = -0.307(453), p < .05$, indicating that for a small part of the FAA, an increase in landscape fragmentation is associated with a decrease in the duration of the fire season. Although it seems logical to expect that landscape fragmentation should be an inhibitor of all fire regime parameters, the reasons are not obvious when considering fires across the entire FAA. The relatively low percentage of shared variation (9.4%) points to the possibility that this correlation either occurs at randomly scattered locations across the FAA, or holds true in one or two confined parts of the FAA only.

There is a moderately strong negative relationship between FSD and bush density, $r_s = -0.472(453), p < .05$. Why should an increase in bush density be associated with a decrease in FSD? As was the case with landscape fragmentation, it is probable that this relationship is caused by an associated land use practice which is actually responsible for the correlation.

There are moderately strong positive correlations between FSD and rainfall, Max NDVI, Mean NDVI, NDVI green-up rate and total NDVI, $r_s = 0.480, 0.467, 0.489, 0.194$ and $0.495$ respectively, $(453), p < .05$. The relationship between FSD and the peak of the growing season is weak and negative, $r_s = -0.197(453), p < .05$. It is therefore clear that an increase in rainfall, with its resultant increase in NDVI values which signify an increased biomass production, is strongly associated with an extended fire season. From a biophysical perspective, this could be explained by the fact that the increased availability of fuels allows burning for longer periods of time. Additionally, the high rainfall areas are associated with an early onset of the rainy season, followed by a relatively early peak. For instance, in the Caprivi region, the rainy season peaks between January and March (figure 4.4.10f). This allows up to six months for fuel curing and burning before the next greening up cycle starts in September or October (figure 4.4.10h). The negative correlation between FSD and the NDVI peak month is ascribed to the fact that a late peak to the growing season would be a result of a late peak in the rainy season, which in turn leaves fewer months for curing of fuel and a fire season.
7.4.3 Fire season peak

Converted correlation coefficient values, showing the percentage of shared variability between variables are shown in table 7-4. The fire season peak is significantly correlated with human population density, livestock density, bush density, landscape fragmentation, and rainfall. All correlations are weak or very weak, indicating a rather tenuous association between the variables.

<table>
<thead>
<tr>
<th>Variability shared with Fire Season Peak (%)</th>
<th>5.2</th>
<th>2.6</th>
<th>1.8</th>
<th>2.8</th>
<th>1.0</th>
<th>0.4</th>
<th>0.4</th>
<th>0.5</th>
<th>0.1</th>
<th>0.0</th>
</tr>
</thead>
</table>

Table 7-4 Converted correlation coefficient values, showing the percentage shared variability between the Fire Season Peak (FSP) and the Land Use/Environmental variables. Note that the numbers represent shared variability between pairs, e.g. FSP and Rainfall, FSP and Max NDVI, FSP and Bush Density etc. It does not account for the contribution of other variables, and therefore the % variability row will not sum to 100.

There is a weak negative correlation between the FSP and population density, livestock density and landscape fragmentation, $r_s = -0.227$, -0.161 and -0.133 respectively, (453), $p < .05$. The weakness of these relationships, as reflected by the low percentage of shared variability shown in table 7-4, indicates that for a very small part of the FAA, a shift towards late season burning is associated with a decrease in human population and livestock density as well as a decrease in landscape fragmentation. This is supported by comparing figures 1.4.1 (p8) and 5.2.3 (p75), which show the spatial distribution of populated areas and season of burning respectively. The overlap between low population density and late burning is clear.

The FSP has a weak positive association with bush density, $r_s = 0.166(453)$, $p < .05$, signifying that for a relatively small part of the FAA, an increase in bush density is associated with later burning.
There is a very weak negative association between FSP and rainfall, \( r_s = -0.098(453), p < .05 \). For a very small part of the FAA therefore, later burning is associated with lower rainfall.

7.4.4 Area burned

Converted correlation coefficient values, showing the percentage of shared variability between variables are shown in table 7-5. The fire season peak is significantly correlated with all variables except NDVI green-up rate.

<table>
<thead>
<tr>
<th>Variability shared with Area Burned (%)</th>
<th>Population density</th>
<th>Livestock density</th>
<th>Landscape fragmentation</th>
<th>Bush density</th>
<th>Rainfall</th>
<th>Max NDVI</th>
<th>Mean NDVI</th>
<th>NDVI Green-up</th>
<th>NDVI total</th>
<th>NDVI peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>9.9</td>
<td>23.1</td>
<td>15.7</td>
<td>11.6</td>
<td>7.8</td>
<td>9.4</td>
<td>0.4</td>
<td>9.6</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

*Table 7-5 Converted correlation coefficient values, showing the percentage shared variability between the Area Burned (AB%) and the Land Use/Environmental variables. Note that the numbers represent shared variability between pairs, e.g. AB and Rainfall, AB and Max NDVI, AB and Bush Density etc. It does not account for the contribution of other variables, and therefore the % variability row will not sum to 100.*

The correlation between the size of the area burned (AB%) and the human population density is weak and negative, \( r_s = -0.143(453), p < .05 \). An increase in human population density is therefore associated with a decrease in the AB%. This is accompanied by moderately strong negative correlations with livestock density as well as with landscape fragmentation, \( r_s = -0.314 \) and \(-0.418\) respectively(453), \( p < .05 \). As mentioned previously, human population density is positively correlated with livestock density and landscape fragmentation. Of the three variables, landscape fragmentation shares the highest percentage of variability with the AB%. This would seem to indicate that it is a more widespread association than human or livestock density.

Bush density is moderately and negatively correlated with the size of the AB%, \( r_s = -0.396(453), p < .05 \). Thorn bush savanna species and grasses compete for available
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nutrients (Mopipi et al 2009). Areas with higher bush densities would therefore have lower grass fuel loads, which in turn could lead to smaller burn fractions.

There is a moderately strong positive correlation between the extent of the burned area and rainfall, Max NDVI, Mean NDVI and Total NDVI, \( r_s = 0.341, 0.279, 0.307 \) and 0.310 respectively, \( p < 0.05 \). As discussed earlier, the linear relationship that exists in savanna areas between rainfall and vegetation biomass production, means that areas that receive more rain will produce more fuel which can form a continuous fuel bed that carries fire across the landscape.

7.5 Relationships within land use types

QDSs that have their centres within a particular land use types were selected for correlation analysis within each of the eight land use types. This resulted in a variable number of squares being selected as determined by the spatial extent of the land use type. Numbers ranged from 181 QDSs for the largest category – small scale agriculture on communal land – to 5 QDSs for the smallest category – urban. For the QDSs of each land use type, the analysis described in section 7.4 was replicated by pairing the fire return period, fire season duration, peak month for the fire season, and area burned with human population density, livestock density, landscape fragmentation, bush density, rainfall, maximum NDVI value, mean NDVI value, NDVI greening up rate, peak month of NDVI, and sum of NDVI values.

The results of the correlation analysis for each of the eight land use categories described in chapter 6 are given in appendix 5. For the purpose of this study, only the four large land use categories will be discussed. These are LUC-1, LUC-2, LUC-3 and LUC-6 representing agriculture and tourism on freehold land; large scale agriculture on communal land; small scale agriculture on communal land; and state protected land respectively. Together, these four land use types cover 93.7% of the country. The four discounted categories are either very small and widely scattered, or fall largely outside the FAA. Three of these categories each cover less than 1% of the country’s area and are therefore not able to influence the fire regimes in a significant way.
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7.5.1 LUC-1 Agriculture and tourism on freehold land

The correlation coefficients for the four fire regime characteristics and the land use/environmental parameters for this land use category are shown in table 7-6. Correlations that are not significant have been omitted, while anomalies are shown in bold green.

<table>
<thead>
<tr>
<th></th>
<th>Fire return period</th>
<th>Fire season duration</th>
<th>Fire season peak</th>
<th>Area burned (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>-0.310</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Livestock density</td>
<td>-0.190</td>
<td>-0.181</td>
<td>-0.361</td>
<td></td>
</tr>
<tr>
<td>Landscape fragmentation</td>
<td>-0.165</td>
<td></td>
<td>-0.166</td>
<td></td>
</tr>
<tr>
<td>Bush density</td>
<td>-0.196</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>-0.363</td>
<td>-0.161</td>
<td>-0.177</td>
<td></td>
</tr>
<tr>
<td>Max NDVI</td>
<td>-0.413</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean NDVI</td>
<td>-0.347</td>
<td>-0.189</td>
<td>-0.263</td>
<td></td>
</tr>
<tr>
<td>NDVI green-up rate</td>
<td>-0.353</td>
<td></td>
<td>0.245</td>
<td></td>
</tr>
<tr>
<td>NDVI total</td>
<td>-0.364</td>
<td>-0.133</td>
<td>0.025</td>
<td>-0.283</td>
</tr>
<tr>
<td>NDVI peak</td>
<td>0.241</td>
<td>0.035</td>
<td>0.029</td>
<td>0.295</td>
</tr>
</tbody>
</table>

Table 7-6 Spearman rho values for fire regime characteristics and land use/environmental parameters for LUC-1. Direction changes are shown in bold green. Only significant correlations are shown.

As can be seen in table 7-6, anomalies abound in this land use type, with almost half of the significant correlations showing changes in direction. More importantly, the direction changes for the FRP are all confined to the relationship between the FRP and land use parameters, while the anomalous values for FSD and AB% are confined to the environmental parameters.

Contrary to expectations based on relationships uncovered for the entire FAA (section 7.4.1), an increase in the time interval between burning is weakly associated with a decrease in livestock density, bush density and landscape fragmentation, \( r_s = -0.190, -0.165 \) and -0.196 respectively, (156), \( p < .05 \). At the same time, an increase in the duration of the fire season is weakly associated with decreasing rainfall, mean NDVI and total NDVI, as well as a shift of the NDVI peak towards later in the year, \( r_s = -0.161, -0.189, -0.133 \) and 0.035 respectively, (156), \( p < .05 \). Similarly, an increase in the percentage of the area burned is weakly associated with decreasing rainfall, mean NDVI and total NDVI, as well as a shift of the NDVI peak towards later in the year, \( r_s = -0.177, -0.263, -0.283 \) and 0.295 respectively, (156), \( p < .05 \).
7.5.2 LUC-2 Large scale agriculture on communal land

The correlation coefficients for the four fire regime characteristics and the land use/environmental parameters for this land use category are shown in table 7-7. Correlations that are not significant have been omitted, while anomalies are shown in bold green.

<table>
<thead>
<tr>
<th></th>
<th>Fire return period</th>
<th>Fire season duration</th>
<th>Fire season peak</th>
<th>Area burned (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>0.468</td>
<td>-0.461</td>
<td></td>
<td>-0.586</td>
</tr>
<tr>
<td>Livestock density</td>
<td>0.566</td>
<td>-0.617</td>
<td></td>
<td>-0.630</td>
</tr>
<tr>
<td>Landscape fragmentation</td>
<td>0.536</td>
<td>-0.434</td>
<td></td>
<td>-0.504</td>
</tr>
<tr>
<td>Bush density</td>
<td>0.517</td>
<td>-0.488</td>
<td>0.396</td>
<td>-0.456</td>
</tr>
<tr>
<td>Rainfall</td>
<td>-0.781</td>
<td>0.648</td>
<td></td>
<td>0.394</td>
</tr>
<tr>
<td>Max NDVI</td>
<td>-0.686</td>
<td>0.566</td>
<td></td>
<td>0.332</td>
</tr>
<tr>
<td>Mean NDVI</td>
<td>-0.820</td>
<td>0.758</td>
<td></td>
<td>0.571</td>
</tr>
<tr>
<td>NDVI green-up rate</td>
<td>-0.448</td>
<td>-0.353</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDVI total</td>
<td>-0.813</td>
<td>0.750</td>
<td></td>
<td>0.530</td>
</tr>
<tr>
<td>NDVI peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7-7 Spearman rho values for fire regime characteristics and land use/environmental parameters for LUC-2. Direction changes are shown in bold green. Only significant correlations are shown.

For this land use category, the only anomalies are in the correlation between human population density and the FRP, and between human population density and the FSD. An increase in human population density is moderately associated with an increase in the period between fires and a decrease in the duration of the fire season, $r_s = 0.468$ and -0.461 respectively, (156), $p < .05$. This is contrary to the association that exists across the FAA and is also anomalous with LUC-1.

7.5.3 LUC-3 Small scale agriculture on communal land

The correlation coefficients for the four fire regime characteristics and the land use/environmental parameters for this land use category are shown in table 7-8. Correlations that are not significant have been omitted, while anomalies are shown in bold green. This land use category is the largest of the four under consideration, and covers most of the fire affected areas of Namibia. It is therefore natural to assume that relationships that apply to the FAA will hold true here. From table 7-8 it is clear that this is indeed the case, with only one exception: an increase in landscape fragmentation is weakly associated with an increase in the length of the fire season, $r_s = 0.147$, (181), $p < .05$. 

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Table 7-8 Spearman rho values for fire regime characteristics and land use/environmental parameters for LUC-3. Direction changes are shown in bold green. Only significant correlations are shown.

<table>
<thead>
<tr>
<th></th>
<th>Fire return period</th>
<th>Fire season duration</th>
<th>Fire season peak</th>
<th>Area burned (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>-0.187</td>
<td>0.239</td>
<td>-0.269</td>
<td></td>
</tr>
<tr>
<td>Livestock density</td>
<td>-0.167</td>
<td>-0.166</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscape fragmentation</td>
<td>-0.147</td>
<td>-0.154</td>
<td>-0.261</td>
<td></td>
</tr>
<tr>
<td>Bush density</td>
<td>0.620</td>
<td>-0.482</td>
<td>0.380</td>
<td>-0.260</td>
</tr>
<tr>
<td>Rainfall</td>
<td>-0.768</td>
<td>0.692</td>
<td>-0.270</td>
<td>0.482</td>
</tr>
<tr>
<td>Max NDVI</td>
<td>-0.719</td>
<td>0.703</td>
<td></td>
<td>0.458</td>
</tr>
<tr>
<td>Mean NDVI</td>
<td>-0.690</td>
<td>0.675</td>
<td></td>
<td>0.474</td>
</tr>
<tr>
<td>NDVI green-up rate</td>
<td>-0.406</td>
<td>0.421</td>
<td></td>
<td>0.180</td>
</tr>
<tr>
<td>NDVI total</td>
<td>-0.660</td>
<td>0.659</td>
<td></td>
<td>0.471</td>
</tr>
<tr>
<td>NDVI peak</td>
<td>0.230</td>
<td>-0.223</td>
<td></td>
<td>-0.176</td>
</tr>
</tbody>
</table>

7.5.4 LUC-6 State protected

The correlation coefficients for the four fire regime characteristics and the land use/environmental parameters for this land use category are shown in table 7-9. Correlations that are not significant have been omitted, while anomalies are shown in bold green. The correlations for this land use category are in line with those of the FAA. There are no anomalies.

Table 7-9 Spearman rho values for fire regime characteristics and land use/environmental parameters for LUC-6. Direction changes are shown in bold green. Only significant correlations are shown.

<table>
<thead>
<tr>
<th></th>
<th>Fire return period</th>
<th>Fire season duration</th>
<th>Fire season peak</th>
<th>Area burned (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>-0.346</td>
<td>0.330</td>
<td>-0.379</td>
<td></td>
</tr>
<tr>
<td>Livestock density</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscape fragmentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bush density</td>
<td>0.901</td>
<td>-0.764</td>
<td>0.503</td>
<td>-0.504</td>
</tr>
<tr>
<td>Rainfall</td>
<td>-0.777</td>
<td>0.859</td>
<td>-0.449</td>
<td>0.368</td>
</tr>
<tr>
<td>Max NDVI</td>
<td>-0.885</td>
<td>0.908</td>
<td>-0.561</td>
<td>0.445</td>
</tr>
<tr>
<td>Mean NDVI</td>
<td>-0.877</td>
<td>0.911</td>
<td>-0.529</td>
<td>0.499</td>
</tr>
<tr>
<td>NDVI green-up rate</td>
<td>-0.801</td>
<td>0.818</td>
<td>-0.630</td>
<td>0.302</td>
</tr>
<tr>
<td>NDVI total</td>
<td>-0.830</td>
<td>0.864</td>
<td>-0.516</td>
<td>0.458</td>
</tr>
<tr>
<td>NDVI peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.6 Discussion

These anomalies beg the question: “How is it possible for land use to affect fire regime parameters so dramatically?”. The ability to bring about these changes implies a significant degree of control over fire events. In the absence of land use, the natural order would be for fires to follow the same pattern of frequency, timing and extent as dictated by the climatic parameters.

What is it then about LUC-1 in particular, that enables the control that allows such substantial deviation from the norm? The answer probably lies in the way in which land management is applied within a land use category, as well as the land tenure associated with the land use category. Legal private ownership of the land is usually associated with the erecting of boundary fences to demarcate the boundaries of the farm, and to keep own livestock in and others’ out. The farm is then sub-divided by means of internal fences into a number of paddocks or “camps” to facilitate animal husbandry. Each farm typically covers an area of between 5000 and 10000 hectares and has one main homestead. This arrangement is depicted in figure 7.6.1 which shows farmland around the town of Otjiwarongo in central Namibia. With this infrastructure in place, it is possible to alter the available fuel load quite
dramatically, as illustrated by figure 7.6.2. This level of land management cannot be applied to rangelands in a communal system, where livestock are either herded or left to range freely in an open access system (figure 7.6.3). Furthermore, the level of infrastructure in the form of roads and tracks is unprecedented. Not only are there networks of roads connecting farms to each other and to towns, but on any given farm there will be an internal network of roads and tracks connecting the homestead with water points in each camp. Additionally, every fence line will have a maintenance road or track running adjacent to it. The spatial arrangement of regular sized farming units also gives rise to a sparsely populated but evenly distributed human population (figure 7.6.4) which is able and willing to react quickly to put out fires on their or a neighbour’s property. This contrasts starkly with the situation in the communal areas, where populations are clustered, road networks are poor, and the farmer does not have deed and title to the land. Given this limited infrastructural development, it is not only difficult for the community to reach a fire that needs to be controlled, but since they do not actually own the resource that is threatened by the fire, the perceived need to react is probably weak or absent.

7.7 Summary

Correlation analysis shows the degree to which ordinal scale data co-vary. It does not imply a causal relationship between the variables. Less than perfect correlations are often the result of other factors such as common and indirect influences. Spearman’s rank correlation coefficients were calculated for fire return period, fire season duration, peak month for the fire season, and area burned paired with human population density, livestock density, landscape fragmentation, bush density, rainfall, maximum NDVI value, mean NDVI value, NDVI greening up rate, peak month of NDVI, and sum of NDVI values.
For the fire affected area as a whole, there are significant correlations between all of the variables, except for fire season peak and the NDVI variables. This confirms a degree of independence between the time of year when the most burning takes place, and the production of the biomass that is consumed. There is also no significant correlation between the NDVI green-up rate and the extent of burning. When considering the four spatio-temporal fire characteristics - FRP, FSD, FSP and AB%, the strongest correlations are between:

- FRP and RF(-); FRP and Mean NDVI(-); FRP and Total NDVI(-), showing that an increase in rainfall (and therefore NDVI) is associated with more frequent burning.
- FSD and Bush Density(-); FSD and RF(+); FSD and Max NDVI(+); FSD and Mean NDVI(+), showing that an increase in rainfall (and therefore NDVI) is associated with a lengthening of the fire season which is mitigated or inhibited by an increase in bush density.
- FSP and Human Population Density(-), showing that an increase in human population density is associated with an earlier peak to the burning season. Although this was the strongest relationship, it was still statistically weak while the remainder were very weak or not significant.
- AB% and Landscape Fragmentation(-); AB% and Livestock Density(-); AB% and Bush Density(-); AB% and Rainfall(+), showing that an increase the area burned is associated with an increase in rainfall, but that this effect is reduced by landscape fragmentation, bush density and livestock grazing pressure.

There is a marked difference in the correlations between the spatio-temporal fire characteristics and the land use/environmental parameters within different land use categories. One category in particular, LUC-1 - Agriculture and Tourism on Freehold Land, differs radically from the rest. The reasons for this is not so much a case of land use directly affecting the fire environment, but it provides the farmers with the ability to control fire events - an ability that stems from a highly developed road network, combined with a mobile community who perceives every fire as a threat and is prepared to come together to fight it at all costs.
8 CONCLUSION

In recent years, it has become fashionable to start a publication, presentation or speech about fire with “Biomass burning is becoming more widespread and fires are occurring with increasing frequency”. This sweeping statement is often made in the absence of any real data with which to back it up. The proliferation of Earth observation satellites since the middle of the 1900’s have allowed the remote sensing community to monitor global biomass burning like never before. However, these 60 years of monitoring span only 0.00001% of the time covered by biomass burning - equivalent to measuring the last 50 seconds of an event that started 11 years ago. This perspective on our insignificant efforts in no way detracts from our desire to understand the nature of fire regimes - indeed, it lends weight to the importance of qualifying our statements with facts and figures.

While global and in some cases continental fire studies provide information on aspects of fire regimes, the information is not directly down-scalable to the national level. For this reason, local data on the where, when, how much and how often of biomass burning remains elusive. Nevertheless, the perceived need to eradicate fire from the African landscape dictates that policy be formulated as a matter of urgency - often based on strong preconceptions rather than strong research findings. Fires in the Namibian savannas are probably as old as anywhere in Africa, but the regimes have never been described. Similarly, the influence of land use on fire regimes has not been investigated, despite striking differences in some fire aspects between different land use areas.

This study therefore set out to address these issues, as outlined in the introductory chapter. On a different level, this study also had as its aim, the development of two complimentary data processing tools that could be installed on a PC and used to provide a fire monitoring service. This thesis document not only presents the findings of the study, but is intended as a broader reference work on fire in Namibia.
8.1 Achievements

This study provides the first complete characterisation of fire regimes in Namibia. In order to achieve this, two semi-automated systems were developed:

- An Excel based tool for the extraction of a range of metrics from a 10 year time-series of burned area maps.
- An Excel based tool for the extraction of a range of metrics from a 10 year time-series of vegetation index maps.

This study also provides the first quantification of the relationships between land use parameters and spatio-temporal fire regime characteristics in Namibia.

Either one of these achievements makes an important contribution to the understanding of burning issues in Namibia - an understanding that should form a crucial component of the policy formulation process.

8.2 Outlook

The key finding of this study is perhaps not so much that the correlations generally confirm what we suspected, but that it is possible to detect these correlations with such a coarse system - already low resolution AVHRR data resampled to a MMU of a quarter degree, matched with “best estimate/first approximation” Namibia Atlas data.

With improved satellite data and more detailed ground information, the results can only get better. This study covers a 10 year period which ended almost 10 years ago. Since then, the MODIS instrument onboard NASA’s Aqua and Terra satellites has been providing data of much higher fidelity than was used in this study. Although MODIS based global burned area detection algorithms are still not useable at the national level, the images data can be used for improved spatial resolution burned area mapping using the method described in this study. MODIS also provides matching NDVI data that can be used by the spreadsheet tool to extract phytophenological milestones.

There is a real need to not only extend the analysis from 2003 to the present, but to
continue the monitoring on an annual basis as part of an ongoing contribution to our understanding of fires in Namibia.

As mentioned in the introduction to this thesis (page iii), the need for National level studies remain. Policies which are able to influence biomass burning are formulated per country, not per subregion or biome or vegetation type. In the absence of national fire statistics, some countries might have no alternative but to use regional fire regime statistics where those are available. This approach is not advisable, since the relationships that exist at one level may be very different at another level. This was illustrated clearly in chapter 7, where correlations that were positive at the national level become negative at the LUC level and vice versa. The same seems to be true when scaling down from regional to national level. For instance, Archibald et al (2010) found that their findings supported previous studies that show a fire season progression from northwest to southeast. In Namibia, the progression is exactly the opposite, with the season starting with early burns in the northeast, and concluding with late season burns in the southwest. Similarly, across southern Africa, the season of burning as well as the fire return time is not affected by land use/human impact (Archibald et al 2010).

This is not applicable to Namibia, where human impact/landscape fragmentation was found to be negatively correlated with the season of burning, and positively correlated with the fire return period. Furthermore, at the actual Namibian land use category level, some of these relationships invert while others become insignificant, again highlighting the importance of local level analysis over the downscaling of regional statistics. It is possible that some of these anomalies arise from different definitions of the term land use, or different ways of calculating the fire return period, but the fact remains that the resulting statistic cannot be blindly applied to any given country in the region.

This study would have made Veblen proud, because many questions are now growing where only a few grew before. These questions can be split into two groups:

1. Those that are concerned with the meaning of the actual statistics derived from the datasets.

2. Those that are concerned with the effect that errors, accuracy and precision have on the derived statistics.
Perhaps the most meaningful approach would be to undertake in-depth high resolution studies into hotspots identified by this study, in order to find answers to questions such as:

- What are the quantifiable effects of frequent late season burning on the woodlands of north-eastern Namibia?
- What socio-economic and or land use related factors are driving the fire regime trends?
- Which of the land use and environmental factors that are correlated with fire regime parameters are the most important?
- How are these correlated factors inter-related?
- How important (ecologically) are inter-annual variations?

In response to the second aspect, technical questions which arise are:

- How different would the statistics be when using a smaller or larger MMU?
- At what spatial threshold are the relationships affected?
- What effect does the MAUP have on the statistics?

Other questions come to mind, but some should remain to be discovered by the reader.

---

*I checked it very thoroughly,* said the computer, *‘and that quite definitely is the answer. I think the problem, to be quite honest with you, is that you’ve never actually known what the question is.’*

References


APPENDIX 1

The processing routine that was written for the Etosha Ecological Institute, in order to simplify pre-processing of AVHRR block files before the development of the NOM.

Explanations are given in red. Commands which are executed by the batch routine are shown in black.

This routine will run if:

It is saved as a text file,
The text file’s extension is changed from .txt to .bat
All the executables are present in the appropriate directories
Each explanatory line (red print) is either deleted or preceded by a rem

@echo off
Ensures that instructions are only displayed on the screen when this program tells it to.
cls
Clears the screen.
\cd\noaa\images\current
Changes to the noaa\images\current directory.
Call map_move
Runs a program called map_move.exe, which allows you to perform the initial geometric correction on the blockfile by fitting a map overlay to the image.
echo.
echo.
"Echo" followed by a full stop prints a blank line on the screen.
echo Now producing a channel 2 image from %1 ..... Statements after "echo" are echoed (printed) to the screen.
%1 refers to the first command line parameter which follows the batch file name. In other words, if you ran this batch file from a DOS window by typing nrscprod and pressing enter, there would be no %1. If you type nrscprod se78b234.3b3 then se78b234.3b3 is %1. If you typed another text string after it that would be %2 and so on.
echo.
chxcal %1 2 0 0.2
Runs a program called chxcal.exe, and specifies command line parameters for it. This produces a calibrated channel 2 image.
echo.
Prints a blank line on the screen.

:prods_ll_chn2
Text strings which start with a colon serve as bookmarks to which you can jump or loop.
prods_ll -17.00 19.4 -19.00 25.60 0.01 0.01
Runs a program called prods_ll.exe, which reprojects the calibrated channel 2 image into a window with the coordinates specified in the command line.

cd c:\tekcor\ext_data
Changes to the tekcor\ext_data directory.
ren lhc2%2.dat chn2%2.img
Renames the reprojected file (called lhc2%2 where %2 corresponds to the second command line parameter for this batch file) to chn2%2 and changes the file extension from .dat to .img. This allows the data in the file to be read by Idrisi.
copy chn2_cap.doc chn2%2.doc
Copies a template documentation (header) file and gives it the same name as the .img file. This file (chn2%2.doc) can be edited in MS Word, Notepad etc.

cd c:\idrisi
Changes to the Idrisi directory.
environ x 1 C: 2 \tekcor\ext_data
Sets the working environment for Idrisi to C:\tekcor\ext_data, because that is where the channel 2 image was written to.
color x a chn2%2 grey256 n 0 0 0 -1 0 -1 CAPRIVI 10
Instructs Idrisi to display the channel 2 image with a 256 colour greyscale pallette, and to overlay a vector layer called Caprivi.

:begin
Bookmark.
cls
Clears the screen.

echo ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Draws a wavy line on the screen.
echo  Is the map overlay on the image satisfactory?
Echoes the question to the screen.
echo.
echo.
Prints two blank lines on the screen.
echo  OPTIONS:
Echoes the text string to the screen.
echo.
Prints a blank line on the screen.
echo  1  YES ... Produce channel 1,2,3,4 & 5 images
Echoes the text string to the screen.
echo.
Prints a blank line on the screen.
echo   OR
Echoes the text string to the screen.
echo.
Prints a blank line on the screen.
echo  2  NO .... re-adjust the map overlay
Echoes the text string to the screen.
echo.
echo.
Prints two blank lines on the screen.
choice /c:12 /n PRESS 1 or 2
Runs a program called choice.exe, which captures user input through the keyboard and stores it as an "errorlevel" variable.
if errorlevel 2 goto mm
Tells this batch routine to jump to the bookmark called “mm” if the user presses the number 2 key.
if errorlevel 1 goto next
Tells this batch routine to jump to the bookmark called “next” if the user presses the number 1 key.

:mm

Bookmark.

cd c:\tekcor\ext_data

Changes directory.

del ???%2.img

Deletes any image files which might have been created. This forces the creation of a new image file, and prevents the batch routine from loading the wrong file.

del ???%2.doc

Deletes documentation (header) files which might have been created, for the same reasons as in the above note.

call map_move

Call the Map_move.exe program again, to allow the user to adjust the map fit.

goto prods_ll_CHN2

Directs this batch routine to loop back to a the “prods_ll_chn2” bookmark.

:next

Bookmark

cd c:\tekcor\ext_data

Changes directory.

del c:\tekcor\ext_data\????%2.*

Deletes all images which were created so far, so as to make a fresh start.

goto day

Directs this batch file to go to the “day” bookmark.

:day

Bookmark.

echo.

Prints a blank line on the screen.

cd \noaa\images\current

Changes directory.
echo Producing channel 1 reflectance image from %1
Echoes the text string to the screen.
chxcal %1 1 0 0.2
Runs the chxcal.exe program, and specifies command line parameters for it. This produces a calibrated channel 1 image.
echo Producing channel 2 reflectance image from %1
Echoes the text string to the scene.
chxcal %1 2 0 0.2
Runs the chxcal.exe program, and specifies command line parameters for it. This produces a calibrated channel 2 image.
echo Producing channel 3 brightness temperature image from %1
Echoes the text string to the scene.
chxcal %1 3 273 0.2
Runs the chxcal.exe program, and specifies command line parameters for it. This produces a calibrated channel 3 image.
echo Producing channel 5 brightness temperature image from %1
Echoes the text string to the scene.
chxcal %1 4 273 0.2
Runs the chxcal.exe program, and specifies command line parameters for it. This produces a calibrated channel 4 image.
echo Producing channel 5 brightness temperature image from %1
Echoes the text string to the scene.
chxcal %1 5 273 0.2
Runs the chxcal.exe program, and specifies command line parameters for it. This produces a calibrated channel 5 image.
echo.
Prints a blank line on the screen.
echo Now Re-Projecting the Images.....
Echoes the text string to the scene.
echo.
Prints a blank line on the screen.
prods_ll -17.00 19.4 -19.00 25.60 0.01 0.01
Runs a program called prods_ll.exe, which reprojects all the calibrated channel images into a window with the coordinates specified in the command line.

`cd \tekcor\ext_data`
Changes directory.

`dir`  
Displays a directory listing of the C:\tekcor\ext_data directory.

`move c:\tekcor\ext_data\lhc1%2.dat C:\nrsc\1%3.img`
Moves the reprojected file (called lhc2%2 where %2 corresponds to the second command line parameter for this batch file) to the c:\noaa\nrsc directory, renames it to 1%3 (where %3 corresponds to the third command line parameter for this batch file) and changes the file extension from .dat to .img. This allows the data in the file to be read by Idrisi.

`move c:\tekcor\ext_data\lhc2%2.dat C:\nrsc\2%3.img`
Does the same for the channel 2 image.

`move c:\tekcor\ext_data\lhc3%2.dat C:\nrsc\3%3.img`
Does the same for the channel 3 image.

`move c:\tekcor\ext_data\lhc5%2.dat C:\nrsc\4%3.img`
Does the same for the channel 4 image.

`move c:\tekcor\ext_data\lhc5%2.dat C:\nrsc\5%3.img`
Does the same for the channel 5 image.

`copy c:\tekcor\ext_data\Chn1_cap.doc C:\nrsc\1%3.doc`
Copies a template documentation (header) file to the c:\nrsc directory, and gives it the same name as the .img file.

`copy c:\tekcor\ext_data\Chn2_cap.doc C:\nrsc\2%3.doc`
Does the same for the next channel.

`copy c:\tekcor\ext_data\Chn3_cap.doc C:\nrsc\3%3.doc`
Does the same for the next channel.

`copy c:\tekcor\ext_data\Chn5_cap.doc C:\nrsc\5%3.doc`
Does the same for the next channel.

`copy c:\tekcor\ext_data\Chn4_cap.doc C:\nrsc\4%3.doc`
Does the same for the next channel.

`del c:\tekcor\ext_data\lhc?%2.*`
Deletes (cleans) the c:\tekcor\ext_data directory of files which are no longer needed.
del c:\tekcor\ext_data\hc%2.*

Deletes (cleans) the c:tekcor\ext_data directory of more files which are no longer needed.

:exit

Bookmark.

cls

Clears the screen.

echo.

echo.

echo.

echo.

Prints blank lines on the screen.

echo WHAT ABOUT THE BLOCKFILE?

Echoes the question to the screen.

echo.

echo.

echo.

echo.

echo.

echo.

Prints blank lines on the screen.

echo 1 Delete it

Echoes the text string to the screen.

echo.

Prints a blank line on the screen.

echo 2 Leave it where it is

Echoes the text string to the screen.

echo.

echo.

echo.

Prints blank lines on the screen.

choice /c:12 in PRESS 1 or 2
Runs a program called choice.exe, which captures user input through the keyboard and stores it as an "errorlevel" variable.

if errorlevel 2 goto exit2

Tells this batch routine to jump to the bookmark called "exit2" if the user presses the number 2 key.

if errorlevel 1 goto del_bloc

Tells this batch routine to jump to the bookmark called "del_bloc" if the user presses the number 2 key.

echo.
echo.

Prints blank lines on the screen.

:del_bloc

Bookmark.

del C:\noaa\images\current*.?B?

Deletes the blockfile from the c:\noaa\images\current directory.

:exit2

Bookmark.

exit

Passes control from this batch file back to the operating system.
APPENDIX 2

BURS Blockfile format. Storing data in this format has the advantage that products can be attached and maintained with the parent data. It is also possible to easily attach ancillary data such as:

- Image acquisition date and time
- TLE information
- Tie point data model parameters
- Calibration coefficient values used for channels 1 & 2
- Averaged onboard calibration coefficient values for channels 3, 4 & 5.
- Details of look-up tables used for conversion of Radiance to Brightness Temperatures.
- Details of non-linearity correction figures
- Nominal values used for satellite altitude
- Earth radius value used for calculating satellite zenith and azimuth angles

The table below shows the basic blocks created by the capture program. Other programs may append other blocks subsequently.

<table>
<thead>
<tr>
<th>BLOCK NAME</th>
<th>Overall Block Length (Bytes)</th>
<th>Channel Numbers</th>
<th>Data Length (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEADER</td>
<td>524</td>
<td>No</td>
<td>512</td>
<td>Basic file information</td>
</tr>
<tr>
<td>TIP_DATA</td>
<td>Varies</td>
<td>No</td>
<td>Number of lines * 1280</td>
<td>Raw TIROS Information Processor data, excl. HRPT data</td>
</tr>
<tr>
<td>CHDATA10</td>
<td>Varies</td>
<td>Yes</td>
<td>Number of lines * number of columns * 2</td>
<td>Raw data for particular AVHRR sensor channel. There will normally be 5 “CHDATA10” blocks.</td>
</tr>
</tbody>
</table>

Continues..

* Reproduced from the NOM User Guide v.4.1
<table>
<thead>
<tr>
<th>BLOCK NAME</th>
<th>Overall Block Length (Bytes)</th>
<th>Channel Numbers</th>
<th>Data Length (Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALDLINE</td>
<td>Varies</td>
<td>No</td>
<td>1 * Number of lines</td>
<td>Data validity indicator</td>
</tr>
<tr>
<td>HIST10BT</td>
<td>1038</td>
<td>Yes</td>
<td>1024</td>
<td>Histogram of values for a particular channel. Normally 5 blocks, one per channel</td>
</tr>
<tr>
<td>TLE_DATA</td>
<td>172</td>
<td>No</td>
<td>160</td>
<td>NORAD Two Line Element orbital data</td>
</tr>
</tbody>
</table>
## APPENDIX 3

Table of variables cross-correlated for the entire fire affected area

<table>
<thead>
<tr>
<th>Variable</th>
<th>FRP</th>
<th>FSD</th>
<th>FSP</th>
<th>AB%</th>
<th>Pop Density</th>
<th>Stock Density</th>
<th>L-scape Fragment</th>
<th>Bush Density</th>
<th>Rainfall Max NDVI</th>
<th>Mean NDVI</th>
<th>Green-up Rate</th>
<th>Integrated NDVI</th>
<th>NDVI Peak Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRP</td>
<td>1.000</td>
<td>-0.5848</td>
<td>0.0707</td>
<td>-0.5489</td>
<td>-0.0953</td>
<td>0.0988</td>
<td>0.4753</td>
<td>0.4918</td>
<td>-0.6949</td>
<td>-0.6144</td>
<td>-0.6333</td>
<td>-0.2113</td>
<td>-0.6386</td>
</tr>
<tr>
<td>FSD</td>
<td>-0.5848</td>
<td>1.0000</td>
<td>-0.1265</td>
<td>0.5086</td>
<td>0.1093</td>
<td>-0.1059</td>
<td>-0.3071</td>
<td>-0.4716</td>
<td>0.4802</td>
<td>0.4674</td>
<td>0.4890</td>
<td>0.1940</td>
<td>0.4949</td>
</tr>
<tr>
<td>FSP</td>
<td>0.0707</td>
<td>-0.1265</td>
<td>1.0000</td>
<td>0.1857</td>
<td>-0.2269</td>
<td>-0.1607</td>
<td>-0.1328</td>
<td>0.1655</td>
<td>-0.0977</td>
<td>-0.0665</td>
<td>-0.0652</td>
<td>-0.0729</td>
<td>-0.0365</td>
</tr>
<tr>
<td>AB%</td>
<td>-0.5489</td>
<td>0.5086</td>
<td>0.1857</td>
<td>1.0000</td>
<td>-0.1426</td>
<td>-0.3140</td>
<td>-0.4814</td>
<td>-0.3963</td>
<td>0.3411</td>
<td>0.2792</td>
<td>0.3070</td>
<td>0.0665</td>
<td>0.3099</td>
</tr>
<tr>
<td>Pop Density</td>
<td>-0.0953</td>
<td>0.1093</td>
<td>-0.2269</td>
<td>-0.1426</td>
<td>1.0000</td>
<td>0.7062</td>
<td>0.2367</td>
<td>-0.0310</td>
<td>0.1578</td>
<td>0.1015</td>
<td>0.1017</td>
<td>0.1201</td>
<td>0.0868</td>
</tr>
<tr>
<td>Stock Density</td>
<td>0.0988</td>
<td>-0.1059</td>
<td>-0.1607</td>
<td>-0.3140</td>
<td>0.7062</td>
<td>1.0000</td>
<td>0.2759</td>
<td>0.0884</td>
<td>0.0224</td>
<td>0.0075</td>
<td>0.0245</td>
<td>0.0914</td>
<td>0.0052</td>
</tr>
<tr>
<td>L-scape Fragment</td>
<td>0.4753</td>
<td>-0.3071</td>
<td>-0.1328</td>
<td>-0.4814</td>
<td>0.2367</td>
<td>0.2759</td>
<td>1.0000</td>
<td>0.4396</td>
<td>-0.3291</td>
<td>-0.1412</td>
<td>-0.2577</td>
<td>0.2780</td>
<td>-0.3132</td>
</tr>
<tr>
<td>Bush Density</td>
<td>0.4918</td>
<td>-0.4716</td>
<td>0.1655</td>
<td>-0.3963</td>
<td>-0.0310</td>
<td>0.0884</td>
<td>0.4396</td>
<td>1.0000</td>
<td>-0.1468</td>
<td>-0.0806</td>
<td>-0.1429</td>
<td>0.1287</td>
<td>-0.1656</td>
</tr>
<tr>
<td>Rainfall</td>
<td>-0.6949</td>
<td>0.4802</td>
<td>-0.0977</td>
<td>0.3411</td>
<td>0.1578</td>
<td>0.0224</td>
<td>-0.3291</td>
<td>-0.1468</td>
<td>1.0000</td>
<td>0.8521</td>
<td>0.8767</td>
<td>0.3074</td>
<td>0.8650</td>
</tr>
<tr>
<td>Max NDVI</td>
<td>-0.6144</td>
<td>0.4674</td>
<td>-0.0665</td>
<td>0.2792</td>
<td>0.1015</td>
<td>0.0075</td>
<td>-0.1412</td>
<td>-0.0806</td>
<td>0.8521</td>
<td>1.0000</td>
<td>0.9614</td>
<td>0.5372</td>
<td>0.9203</td>
</tr>
<tr>
<td>Mean NDVI</td>
<td>-0.6333</td>
<td>0.4890</td>
<td>-0.0652</td>
<td>0.3070</td>
<td>0.1017</td>
<td>0.0245</td>
<td>-0.2577</td>
<td>-0.1429</td>
<td>0.8767</td>
<td>0.9614</td>
<td>1.0000</td>
<td>0.3437</td>
<td>0.9736</td>
</tr>
<tr>
<td>Green-up Rate</td>
<td>-0.2113</td>
<td>0.1940</td>
<td>-0.0729</td>
<td>0.0665</td>
<td>0.1201</td>
<td>0.0914</td>
<td>0.2780</td>
<td>0.1287</td>
<td>0.3074</td>
<td>0.5372</td>
<td>0.3437</td>
<td>1.0000</td>
<td>0.2884</td>
</tr>
<tr>
<td>Integrated NDVI</td>
<td>-0.6386</td>
<td>0.4949</td>
<td>-0.0365</td>
<td>0.3099</td>
<td>0.0868</td>
<td>0.0052</td>
<td>-0.3132</td>
<td>-0.1656</td>
<td>0.8650</td>
<td>0.9203</td>
<td>0.9736</td>
<td>0.2884</td>
<td>1.0000</td>
</tr>
<tr>
<td>NDVI Peak Month</td>
<td>0.3088</td>
<td>-0.1973</td>
<td>0.0070</td>
<td>-0.1162</td>
<td>-0.0238</td>
<td>0.0423</td>
<td>0.2231</td>
<td>0.1308</td>
<td>-0.4134</td>
<td>-0.3168</td>
<td>-0.3650</td>
<td>-0.0014</td>
<td>-0.3751</td>
</tr>
</tbody>
</table>
## APPENDIX 4

Table of all paired variables across the entire fire affected area, with $t$ and $p$ values.

<table>
<thead>
<tr>
<th>Pair of Variables</th>
<th>Valid N</th>
<th>Spearman R</th>
<th>t(N-2)</th>
<th>p-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRP &amp; Pop Density</td>
<td>445</td>
<td>-0.095342</td>
<td>-2.0159</td>
<td>0.044414</td>
</tr>
<tr>
<td>FRP &amp; Stock Density</td>
<td>445</td>
<td>0.098800</td>
<td>2.0897</td>
<td>0.037212</td>
</tr>
<tr>
<td>FRP &amp; L-scape Fragment</td>
<td>445</td>
<td>0.475346</td>
<td>11.3718</td>
<td>0.000000</td>
</tr>
<tr>
<td>FRP &amp; Bush Density</td>
<td>445</td>
<td>0.491845</td>
<td>11.8897</td>
<td>0.000000</td>
</tr>
<tr>
<td>FRP &amp; Rainfall</td>
<td>445</td>
<td>-0.694889</td>
<td>-20.3384</td>
<td>0.000000</td>
</tr>
<tr>
<td>FRP &amp; Mean NDVI</td>
<td>445</td>
<td>-0.614389</td>
<td>-16.3895</td>
<td>0.000000</td>
</tr>
<tr>
<td>FRP &amp; Green-up Rate</td>
<td>445</td>
<td>-0.211278</td>
<td>-4.5496</td>
<td>0.000007</td>
</tr>
<tr>
<td>FRP &amp; Integrated NDVI</td>
<td>445</td>
<td>-0.638599</td>
<td>-17.4662</td>
<td>0.000000</td>
</tr>
<tr>
<td>FRP &amp; NDVI Peak Month</td>
<td>445</td>
<td>0.308767</td>
<td>6.8326</td>
<td>0.000000</td>
</tr>
<tr>
<td>FSD &amp; Pop Density</td>
<td>445</td>
<td>0.109323</td>
<td>2.3149</td>
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Table of all paired variables for land use class 1, with t and p values.

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### APPENDIX 6

Table of all paired variables for land use class 2, with t and p values.

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## APPENDIX 7

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