Chapter 16

FIRE REGIMES IN DRYLAND LANDSCAPES

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1. Introduction

Dryland regions are climatically defined through low annual precipitation, with in general dry season periods that can span over several months and take place once or twice a year. A combination of climate and soil characteristics defines the range of likely vegetation composition from grasslands and savannas to dry forests (van Wilgen and Scholes 1997). As these climatic and vegetation characteristics are suitable to recurrent fires, several authors consider such ecosystems as pyrophytic vegetations (Trabaud 1991, Scholes 1997, van Wilgen and Scholes 1997, Mistry 1998, Trollope and Everson 1999, Roques et al. 2001). Fire affects ecosystem dynamics in terms of species selection, regeneration, structure, nutrient cycling, and mortality. While this chapter is devoted to fire regimes, the effects of fires on soil moisture dynamics, infiltration and runoff production are discussed in Chapter 3; the effect on soil nutrient cycling and soil gas emissions are briefly analysed in Chapters 11 and 14. Additional discussion on the role of fire dynamics on different biomes, e.g. grasslands, shrublands, dry forests and savannas, can be found in Chapters 12, 13, and 15.

The concept of fire regime includes several features, related to space and time, characterizing fires typically occurring in a given regional ecosystem such as the fire extent, the frequency, the cycle, the season of burning and the fire behaviour (Whelan 1995).

While these pyrophytic ecosystems are distributed on all continents, this chapter will focus on few ecosystems selected from Africa, southern America, and Europe.

In the southern African region dominated by the savanna biome, where annual precipitation is less than about 600 mm, semi-arid vegetation presents woody species (trees and shrubs) with small and thin broadleaves. In particular, vegetation in Namibia and Botswana is dominated by *Acacia* species and "sweet" or palatable grasses for livestock, i.e. grass with low fiber content and winter sequestration of nutrients in their leaves (Scholes 1997). On the contrary, where rainfall is higher than 600 mm, vegetation is characterized by large broadleaved trees species and "sour" grasses having higher fiber content. In Zambia and Tanzania, forests are mainly represented by Miombo characterized by *Brachystegia* and *Isoberlina* species.

In the tropical climate region of the South American continent, cerrado (a complex vegetation mosaic of savannas, grasslands, and dry forests (Kauffman et al. 1994, Mistry 1998)) is representative of dryland ecosystems and it is widely present in Brazil and Chile. Cerrado results from frequent and successive fires induced naturally by climate but also by anthropogenic activities related to deforestation of the Amazon basin.

In the European Mediterranean region, the typical shrubland ecosystems are the garrigue and maquis, which are similar to the chaparral vegetation in California. Garrigue and maquis differ from their species composition, which reflects differences in soil characteristics and stress tolerance. Those two ecosystems are known in the vegetation succession as transitional stages between grassland and forests mainly dominated by pines and oaks (Trabaud 1989, Vernet 1997, De las Heras et al. 2002). Their dynamics is linked to disturbances such as fires, and they have

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been selected for agricultural and management perspectives and maintained in Mediterranean landscapes for thousands years (Carcaillet et al. 1997, Vernet 1997, Figueiral and Terral 2002, Quilès et al. 2002, Wick et al. 2003).

Thus, the current vegetation composition and structure, such as the openness, of these pyrophytic ecosystems is the result of past and present climates, soil type, and also disturbances such as fires, spreading over these systems with variability in time and space. This chapter will first provide general information about the fire environment and of the combustion process. The different variables characterizing the fire regime will be discussed along with their assessment at different spatial scales. Finally, different fire regimes typical of pyrogenic dryland ecosystems will be described.

2. Fire in its environment

Fire-related processes are controlled by the physics and chemistry of combustion (Whelan 1995). However, a fire starts, spreads, and dies also as the result of three environmental factors, namely vegetation, climate, and topography, which interact together to constitute the natural environment of fire. These three factors and their interactions have already been partially presented in the first section of this book (Sections 2-7). In this chapter, interactions are analysed from the point of view of fire processes.

2.1 COMBUSTION

Energy, initially stored in vegetation during the photosynthesis process, is released during fire as heat when materials such as leaves, grass, or wood are combined with oxygen to form carbon dioxide, water vapour, and other substances (Brown and Davis 1973, Whelan 1995). Three stages in the process of combustion can be recognized in a vegetation fire in relation to the basic principles of combustion physics (Trollope 1984a). These are (i) preheating, in which the fuel just ahead of the fire front is heated, dried, and partly pyrolysed; (ii) flaming combustion, which results from the ignition of the flammable hydrocarbon gases; (iii) glowing combustion, during which the remaining charcoal burns as a solid, with oxidation taking place on the surface, without flame, and leaving a small amount of residual ash. To start, combustion requires the « activation energy » of an external energy source, such as lightning for the dominant natural source, or a human induced source. In the heating process, the fuel moisture is first evaporated (fuel temperatures > 100°C), then cellulose is thermally broken down (pyrolysis), and its breakdown products are volatilised (> 200°C), and ignited to form a visible flame (300 - 400°C) (Johnson 1992). The modes of heat transfer responsible for fire spread from the flaming front are convection and radiation (Figure 1, top). Conduction does not contribute significantly to fire spread because wood and soil are such poor heat conductors. To maintain a solid visible flame, the fire front must be constantly moving to recruit adjacent unburned fuels (Johnson 1992). The moving fire front provides the pilot flame to ignite the unburned vegetation. The flaming combustion ends when most of the volatile compounds have burned. The remaining carbon will eventually burn during the glowing phase. A fire can therefore be considered as a chain reaction, with the initial ignition source providing the activation energy that permits ignition and self-sustainability of a fire (Alexander 1982). The difference between flaming and glowing combustion are of interest to ecologists because they can have different ecological effects (Johnson 1992). For instance, flaming combustion is primarily responsible for plant death and glowing combustion for duff consumption and seedbed preparation.

The combustion process in vegetation fires takes place in a physical environment represented by the vegetation, the climate or weather, and the topography. We will now present these different factors and see how they interact.

2.2 TOPOGRAPHY

Among the abiotic factors, topography presents changes that only occur at the geological temporal scales and therefore it is considered for a given area as a constant and fixed factor in the fire environment. Topography directly and indirectly affects fire ignition and propagation. Hilltops are more affected by lightning than bottom hills or flat terrains. Mid and upper slopes present drier soil conditions and drier vegetation composition due to better water drainage. These dryer conditions favour fire ignition because the combustion of dry vegetation involves less water evaporation and requires less energy before flame occurrence. During the flaming combustion phase, the fire front propagation is facilitated towards uphill direction because the radiation energy released by the flame enhances the pre-heating stage of the adjacent fuel that lies uphill near the flame (Figure 1 bottom). For the same reason, uphill fire will propagate faster than fire spreading on flat or downhill directions.

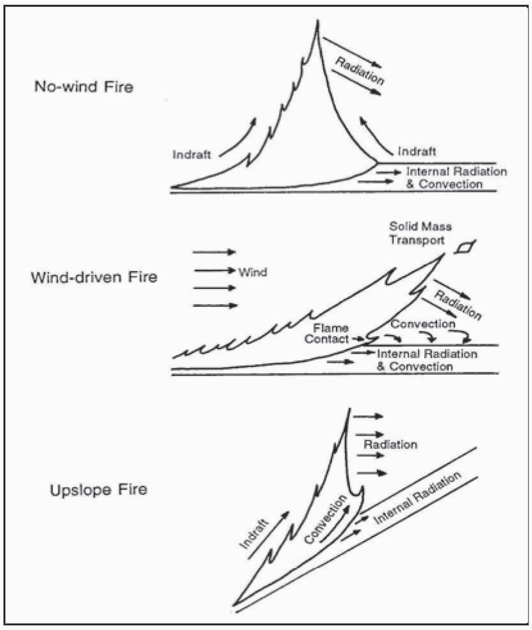

Figure 1. Idealized flaming front with modes of heat transfer. The similar influence of wind and topography on fire behaviour is illustrated in these fire profiles. Both slope and wind bring the flame closer to the adjacent, unburned fuel, so enhancing the pre-heating and increasing the rate of spread (figures from Alexander (1982) Source: Canadian Forest Service, used with permission).

2.3 CLIMATE and WEATHER

Precipitation, temperature, and wind conditions affect the fire at different spatial and temporal scales, through climate at longer term and weather at short term. For a given region, climate, and particularly annual rainfall, determines the main characteristics of dryland landscapes and fire regime. Indeed, climate determines vegetation types, fire season, and fire frequency.

Weather, and especially precipitation, is the most fluctuating factor from days to years in the fire environment (Shroeder and Buck 1970, Trabaud 1991). On a yearly basis, water availability (mostly fed by precipitation) determines the quantity of vegetation and fuel production (van Wilgen and Scholes 1997, Hély et al. 2003b). On a daily basis, weather defines the quality of fuel (moisture content), the fire hazard (dry and windy air), and the fire behaviour. Moisture content in live vegetation changes over the season as the result of plant phenology. Physiological processes, such as stomata closure, prevent vegetation from heating and drying up to a certain stress level at which vegetation dies. Conversely, dead vegetation reacts passively to changes in humidity, and loss of moisture content is faster in thin material than in coarse debris (Burgan and Rothermel 1984, Johnson 1992). Both topography and wind are significant factors for fire spread (Figure 1, middle). Finally, lightning is often associated with first rainfall and thunderstorms at the end of dry seasons, as it provides the perfect natural ignition source for fire triggering.

According to several authors, climate and weather are the most significant factors in determining fire occurrence and fire spread (Bessie and Johnson 1995), though other authors demonstrated that vegetation has to be considered as well (Agee 1997, Hély et al. 2001).

2.4 VEGETATION

Vegetation is the biotic factor providing fuel, and it is characterized in terms of quantity, quality, and spatial arrangement. As previously mentioned, the amount of vegetation is directly related to precipitation quantity, with maximum production for the years with very high precipitation amounts (van Wilgen and Scholes 1997, Hély et al. 2003b). Vegetation growth takes place during the rainy seasons, and as soon as the rain season ends vegetation starts to dry. After few weeks of dry season, vegetation may be dry enough (particularly grasses) to sustain a fire if the minimum fuel load has been reached. In southern African savannas, this minimum fuel load has been estimated at approximately 250-300g/m^2 (van Wilgen and Scholes 1997, Hély et al. 2003a). The size of vegetation particles is also very important as fine debris burn more easily than coarse debris. Therefore, fuels have been classified into diameter classes according to the time lag necessary to loose 2/3 of their saturated moisture content (Brown et al. 1982). One-hour time lag fuel (1-H fuel) is representative of particles whose diameter is less than 0.65 cm and which require only one hour to dry and loose 2/3 of their water content. In the same way, there are 10- and 100-H time lag fuels, which present diameters between 0.65 and 2.5 cm and between 2.5 and 7.6 cm, respectively (Burgan and Rothermel 1984). All grasses, fine woody debris such as small twigs, and litter debris are included in the 1-H time lag class. The 10-H time lag class includes branches of larger diameter, while the 100-H time lag class takes into account small diameter boles and branches less than 8 cm in diameter. Depending on the ecosystem type, larger trunks may not be considered as fuel during the fire front propagation as these pieces are too big and usually still too moist to ignite quickly. However, in many case, if the fire front spreads slowly, or in areas burning against the wind or in the back fire perimeter zone, the residence time of flame can be long enough to ignite these boles that will burn for several hours or days after the fire is over. In such conditions, these large boles and trunks will be completely consumed, leaving only characteristic white ashes on the location of the consumed woody piece. Fuel quality refers both to moisture content and to the chemical composition of vegetation. Indeed, the presence of essential oils and waxes enhance fuel ignition and combustion. Spatial arrangement includes both fuel density and fuel patchiness. The density, which is related to the fuel size and the number of particles, determines the fuel compactness and therefore influences the fire propagation at the local scale. On a larger scale, the patchiness of vegetation types defines the vegetation mosaic, which influences fire propagation through the landscape. This pre-existing patchiness is created by previous fires. This fact suggests the existence of complex interactions and feedbacks between fire and vegetation.

2.5 HUMAN ACTIVITIES

In most dryland regions, anthropogenic activities based on fire use are superimposed over the natural fire environment to create the actual fire environment. Humans are a source of fire ignition caused by their agricultural and hunting activities, or due to accidents. Humans also affect the fire environment through their agricultural and management practices, by changing the fuel availability in terms of quantity, quality, spatial arrangement, and landscape composition. These anthropogenic effects will be further discussed in section 5 through examples from southern African, southern American, and Mediterranean systems.

3. The fire regime and its components

The term fire regime is becoming widely used in the fire ecology literature but it appears to be gaining two denotations: the description of a particular fire or the characterization of fires typically occurring in a given regional ecosystem (Whelan 1995). According to several authors, the second specification should be preferred. The fire regime includes several features related to space and time. Spatial components include the type of fire and its extent, while temporal components relate to the fire frequency, the fire cycle, and the season of burning. Finally the fire behaviour combines both time and space as it includes the fire spread and its intensity. Fire severity is sometimes included in the fire regime definition as the impacts of these above-mentioned variables on the ecosystem in terms of regeneration and resilience. However, in this present chapter, fire severity will not be included in the fire regime definition.

3.1 FIRE TYPE

Fire type describes globally the layer in the vertical structure of the vegetation where the fire spreads. In most dryland regions, the main fuel types are grass, litter, and small shrub layers, with light fuel loads, which generally induce surface fires, running above ground. In regions characterized by Mediterranean vegetation, the vertical fuel structure is more complex as the dominating vegetation layer is composed of shrubs and small trees. In such case, fires can more easily encounter extreme conditions in terms of heavy fuel loads associated with strong winds and low relative humidity. These conditions allow the flame to reach the canopy layer and fire will spread as a crown fire in the tree canopy (Valette 1990, Trabaud 1991). Ground fires, spreading very slowly in deep organic layers of soil, usually without flaming combustion, and over long periods are unusual in dryland regions and restricted to areas such as the Okavango delta and similar landscapes where long-term water presence prevents trees but may favour peatland build up. Fires may be also classified into head fires that burn downwind and/or upslope, and backfires, which burn upwind and/or down slope.

3.2 FIRE EXTENT AND SHAPE

Fire extent is the surface (usually expressed in hectares) burned by a fire. It mainly depends on the stand fuel quality and quantity as well as on the connectivity between stands, and the total heterogeneity of the landscape. To analyse the fire extent patterns in order to reconstruct fire history (linking fire cycle and area), it is necessary to select a landscape size that is larger than the largest fire extent that has ever occurred. Fire extent also depends on the weather conditions taking place over the area when the fire is spreading. Among the weather variables, wind is the most important one in terms of extent and shape. Slope and wind have a synergic effect on burned area when wind blows upwards. Under no-wind conditions in a homogeneous area, the burned scar starting from a point source ignition has a circular perimeter, whereas under windy conditions the fire perimeter has an elliptical shape with the ratio width over length being negatively proportional to the wind speed (Figure 2). Fire breaks (roads, humid areas, lakes and rivers) will influence fire extent and fire shape. Fire extent is the most commonly used and reported variable to describe fire regime for economical and political purposes. However, to better understand the consequences and impacts of fires in a given region, all variables describing fire regime should be taken into account. For instance, large areas burned in grassland savannas will have less ecological and economical consequences than the same areas burned in woody Mediterranean vegetation.

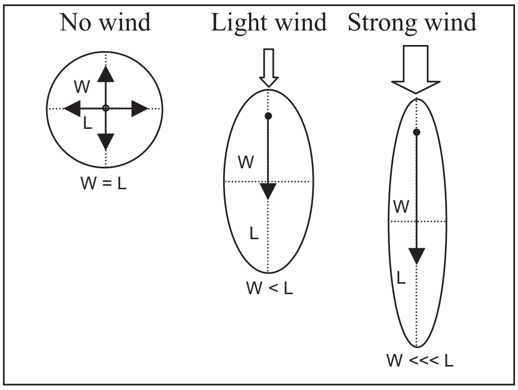

Figure 2. Fire shapes ignited from a point source (·) under different wind conditions in homogeneous fuel bed. Arrows show main direction of the fire front. W is for width, L for length, and r for the ratio W/L, this ratio ranging from 1 under no wind condition to almost 0 under violent winds (from Alexander 1982, Source: Canadian Forest Service, used with permission).

3.3 FIRE FREQUENCY and FIRE CYCLE

The fire frequency for a given area represents the number of fires during a given time unit. Fire cycle is the inverse of fire frequency. Fire cycle is also called fire return or period. For a heterogeneous landscape, the landscape frequency is the sum of the frequencies of each subunit weighted by their area. As an example, Mozambique is one of the southern African countries with high fire incidence. Barbosa *et al.* (1999) estimates that between 18 % and 38 % of the total area of the country is burned annually. Therefore a mean fire cycle in Mozambique may range between 2.5 and 5 years.

Fire frequency depends mainly on two factors: the time required to build up a load of available fuel since the last fire, and the number of potential ignitions. In natural conditions, these ignitions depend on the variability caused by weather during the fire season each year (Whelan 1995). As fire frequency depends on fuel production, it is influenced in African regions by total rainfall (Figure 3) and its inter annual variability (Hély et al. 2003b). Anthropogenic activities may also affect fire frequency through controlled or accidental ignitions, as well as land cover and land use managements. Nevertheless, from the vegetation type classification, average fire frequency can be estimated and positively related to the amount of tree cover and negatively to the total amount of precipitation in African ecosystems. For instance, infertile moist Miombo grasslands, named *Dambo* in Zambia, may burn every year due to heavy rainfall and important grass fuel load. Semi arid grassland and open savannas in Namibia may burn every five years due to high inter annual variability in precipitation, with several consecutive years during which precipitation amounts may not be high enough to produce the minimum fuel load needed to sustain fire spread. As tree cover increases, fuel load is heavier and composition more diverse (tree leaves, twigs, and shrubs) but at the same time the relative humidity also increases, leading to decreasing likelihood of fire ignition and spread. A shift in fire frequency may in turn drastically affect vegetation composition and ecosystem functioning.

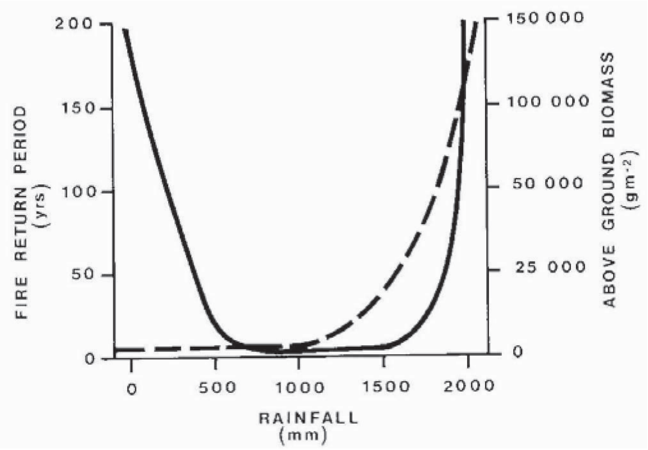

Figure 3. The relationship between rainfall, fuel accumulation (----), and fire frequency (—) in southern African region (van Wilgen and Scholes 1997).

3.4 FIRE SEASON

The fire season describes the season when most fires occur. Fire season is usually related to climate characteristics such as dry seasons in arid regions and to drought periods in more humid regions. However, this natural fire season pattern can be modified by anthropogenic activities. In dryland landscapes, according to the definition mentioned in the beginning of this chapter, fire season corresponds with the dry seasons in terms of number of dry periods where monthly precipitation is less than 50 mm. The length of the fire season is shorter than the length of the dry season because in the early dry season the fuel is still too wet to ignite and to sustain a flame. For instance, natural African fire season is shifted towards the end of the dry season, when lightning, associated with convective storms, reaches extensive areas of vegetation that are dry enough to ignite (Booysen and Tainton 1984, Stott 2000). However, the effective fire season starts few weeks only after the beginning of the dry season due to human ignitions, and it spans all over the dry season due to land management (Stott 2000).

3.5 FIRE BEHAVIOR

The fire behaviour describes the fire propagation mainly in terms of intensity (amount of energy release in kW/m (kJ/s/m)) and rate of spread (rate of energy release that is estimated by the rate of forward movement of the fire front in m/s) (Trollope 1984a). The fire behaviour depends mainly upon weather conditions (wind, air humidity, dew depositing, and air temperature), and fuel load availability and characteristics. Both intensity and rate of spread are usually reported for the fire front line, but both variables can be reported for the flanks and the back of the fire. Backfire intensity is released at the fire perimeter located behind the ignition source point from which fire spreads against the wind and/or downwards the hill. Fire behaviour is one of the fire regime variables, in association with fire season and fire frequency, which is used for land use management through prescribed fires. Such controlled fires are usually applied to reduce fire risk and enhance regeneration.

4. Tools for fire regime analysis

To take into account the aforementioned components of the fire regime characteristic of a given ecosystem type, it is necessary to analyse each of them at the stand and landscape scales.

4.1 GROUND SURVEY AT THE STAND LEVEL

This spatial scale is relevant to analyse the fire type, fire frequency, and fire behaviour. Charcoals trapped in humus, or deposited at the bottom of small surrounding lakes are indicators of past fire events, and provide valuable information for calculation of fire frequency (Carcaillet et al. 1997, Quilès et al. 2002, Thevenon et al. 2003, Wick et al. 2003). When woody vegetation is present (especially trees) fire type can be inferred by looking at the scorch height on the trunks, and at the humus consumption if the last fire was quite recent. Fire scars on trunks reveal also some information about fire frequency and fire behaviour. Indeed, scars generally occur, under windy conditions, on the leeward side of the trunk due to vortex creation that increases the residence time of the flame near the front and enhances hot temperature on that particular side (Gutsell and Johnson 1996). Fire scars reflect therefore the occurrence of fire intensities that are high enough to injure trees, but not enough to kill them. The main wind direction occurring during a fire can be determined when several trees in the burned stand present fire scars in the same direction. One may date the fire that created fire scars by using dendrochronological approaches based on tree ring counting on a transversal trunk section and calibrated series. A main fire event is likely to have occurred when fire scars on different trees within the stand present the same estimated date. Fire frequency is reconstructed through the presence of successive fire scars on a given tree, or on different trees. Variables representative of fire behaviour such as fire intensity, rate of spread and fuel consumption are generally better analysed during experimental prescribed fires. Indeed, pre-fire measurements need to be done in order to estimate fuel load and fuel moisture content before the fire occurs. The instantaneous rate of spread can be then calculated by recording the time the flame spends to reach from one point to another, and repeated instantaneous measurements are averaged over the total length of the fire. Flame length can be related to scorch height on trunks and is measured on different locations to estimate the fire intensity (Alexander 1982).

In National Parks or private properties, managers use prescribed fires during particular periods and for specific targeted objectives (understorey cleaning in forested stands to avoid "ladder fuel" accumulation, early dry season burning to enhance grass regeneration and greenness). They can also use fire behaviour models to estimate potential fire behaviour through the course of the dry season to be aware of risks if fire ignition would occur.

4.2 REMOTE SURVEY AT THE LANDSCAPE LEVEL

Fire cycle, burned areas, and fire shapes need to be analysed at the landscape level in order to provide realistic estimates of the fire regime. Remote sensing approaches (drawing, aerial photography, and more recently satellite images) are relevant techniques to capture spatial and temporal information of vegetation fires. Remote sensing contributes to fire regime studies with: (1) the location of active fires, (2) the assessment of post fire burned area, and (3) of the fire behaviour.

Active fire detection using remote sensing techniques relies on measuring the thermal emission from the combustion process itself (Stroppiana *et al.* 2000). Methods have been developed according to the Plank radiation law (Figure 4): a high temperature body emits radiation more strongly in the shorter wavelength range (shortwave and middle infra-red) than it does at longer infrared wavelength (Stephens and Matson, 1989). The Earth surface at 300°K reaches a maximum emittance at 9.5-µm (thermal infrared), while a burning grass at about 800ºK reaches its maximum emittance at 3.5-µm (Kennedy et al, 1994). Most of detection algorithms have been based on this difference between a shortwave channel very sensitive to hot spots and a longer wave channel relatively insensitive (Figure 4). Main sensors used for active fire detection include the Advanced Along Track Scanning Radiometer (AVHRR) (Giglio *et al.* 1999, Stroppiana *et al.* 2000), the European Space Agency (ESA) Along Track Scanning Radiometer (ATSR, Arino and Rosaz 1999), and the Moderate resolution Imaging Spectroradiometer (MODIS, Justice *et al.* 2002). More recent techniques such as contextual algorithms have been developed to improve the accuracy of fire detection from remote sensing imagery in a global context using a relative threshold based on the statistics of neighbouring pixels (Giglio *et al*, 1999). Such methods are efficient to detect fire occurrence on large areas and they contribute to estimate fire frequency and fire season (Dwyer et al. 2000). However, the timing and spatial extent of burning may not be estimated reliably from active fire detection, as the satellite may not overpass when burning occurs, and clouds may preclude active fire detection (Justice et al. 2002). Moreover, a very small hot spot may saturate the entire pixel, inducing an overestimation of the real burned area. Others methods have been developed for burned area estimation.

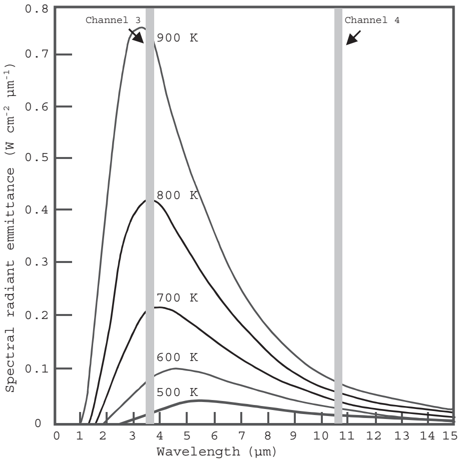

Figure 4. Emittance of a black body at different temperatures according to the Planck radiation Law. A temperature increase produces a greater increase in emitted radiation in shortest infrared wavelengths than it does at longer infrared wavelengths (AVHRR channels3 and 4,respectively). Figure modified from Weaver et al. 1995.

Burned areas are characterized by deposits of charcoals and ashes, by the removal of vegetation, and by the alteration of the vegetation structure (Peirera 1999, Roy et al. 1999). These alterations modify the surface reflectance of such areas (Figure 5), which can be detected from remote sensing (Barbosa et al. 1999, Dwyer et al. 2000, Roy et al. 2002). Several indexes have been used to discriminate between burned and unburned surfaces such as the Normalized Difference Vegetation Index (NDVI) (Salvador et al. 2000), the burn scar index (Roy et al. 1999), the burned area index (Chuvieco et al. 2002), and the normalized burn index (Alleaume et al. in Press)). Recent methods (Roy et al. (2002)) are based on a multi-temporal, multi-threshold approach model of surface reflectance against recent observations of the surface. As soon as fires spread in open dryland areas characterized by a dominant grass layer, the burned area may quickly disappear under windy conditions removing completely ashes, or when the regeneration process starts soon after the fire has occurred. In closed canopy forests, the detection of burned areas is even more difficult when fires are surface fires, because canopies are not affected by fire. When fires affect both grass and trees, due to the scorched foliage, burned areas usually are longer visible than in open grasslands and savannas.

Remote sensing or airborne data are therefore useful to map fire extents and to reconstruct fire map history over dry seasons, and over successive years. They may also provide information on fire spread for fires burning during several consecutive days if the return time is short enough and the residence time over each pixel is long enough. They also improve ground surveys, from which information on each burned area is usually integrated into a Geographic Information System to assist land managers.

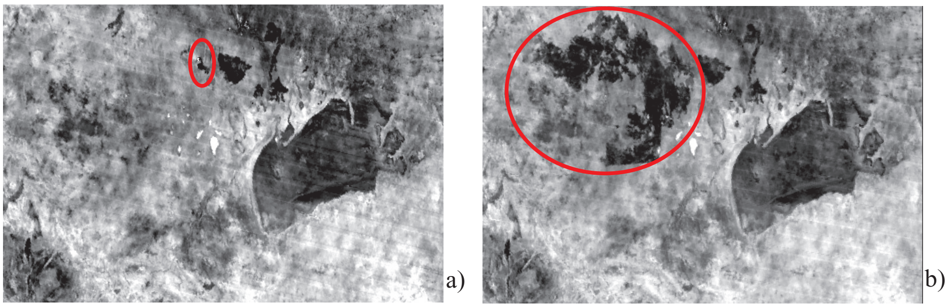

Figure 5. Burned area spreading over Etosha National Park (3000 km^2) in late August 2000. The bean area on the right represents the salt pan of Etosha while the fire is on the northern left region. a) August 24th, b) September 5th 2000.

5. Examples of fire regimes in dryland regions

5.1 SOUTHERN AFRICAN SAVANNAS

It is impossible to determine the beginning of the interactions between man and fire in South African forests and savannas (Granger 1984), however we notice that anthropogenic fires may have been a feature of these ecosystems for the last 150 000 to 180 000 years (Early Stone Age). For a long period, the seasonality of anthropogenic fires was modulated by the life style of both nomadic and sedentary populations. During the Stone Age, nomadic people used fire as a tool to manipulate the environment by opening and maintaining grasslands in a state attractive to the large herds of animals that were hunted, and to possibly induce flushes of edible herbs. As these populations followed the natural phenological cycle of vegetation, there was a lag in fire seasonality between neighbouring regions associated with this migration (Granger 1984). However, because of their low density, these Stone Age populations had probably only a minimal impact, and fire regime was mostly natural (lightning and rock falls ignition sources). Conversely, sedentary populations had a more important impact on vegetation and fire regime. Farmers appeared and settled in this region during the Iron Age. These populations turned to pastoralism and made additional use of fire to clear patches of fertile forest soil for timber exploitation (hut and stockade constructions), food cooking, and to plant crops (Granger 1984, van Wilgen and Scholes 1997, Trollope and Everson 1999). Thus, over approximately the past 4 000 years, man has strongly exploited and disturbed (i.e. burned) these ecosystems, leading to the removal of forest vegetation and to the increase in savanna vegetation (Granger 1984, Vincens et al. 2003). During this period, the anthropogenic contribution to the fire regime has become increasingly more important. Over the last two centuries, fire use regulation in southern African countries has slowly evolved through several stages, including allowance, interdiction, and the use of fire as a management tool in the last few decades. In subsistence agriculture, people use fire throughout the dry season to prepare new fields to cultivate crops such as manioc (*Manihot escultenta* Crantz), which is the basic food for several millions of people. Thus, before cultivating manioc, the people in Zambia practice *Chitemene*, which consists in cutting down and burning all the trees and branches in the middle of a Miombo forested stand and using ashes as a fertilizing bed for crops in the subsequent years before moving to another stand (Holden 1993). They also use fire to favour grass regeneration for livestock feeding. In Namibia or Botswana, where farmers with high number of livestock in semi-arid region practice extensive grazing within very large properties, fire is considered as a competitor of grazing during the dry season (Figure 6). Thus, farmers have attempted to apply fire exclusion in their properties for several consecutive years. However, by increasing the resulting fire frequency, farmers have induced a change in vegetation composition and structure. Less palatable grass species have become dominant over palatable species, and shrub cover has expanded. This phenomenon is known as the "bush encroachment" (Shackleton and Scholes 2000, Hudak and Wessman 2001, Roques et al. 2001, Skowno and Bond 2003). The change in vegetation structure reduced the walking trail allowed to grazing livestock searching for food, and increased woody biomass and total fuel. Therefore, due to the fire exclusion policy, those farms became for a few years extremely susceptible to burning in case of ignition. National Parks such as Etosha national park in Namibia or Kruger national park in South Africa conducted studies on this type of fire management and concluded that fire was necessary for ecosystem dynamics and conservation (Siegfried 1981, Scholes and Walker 1993). Frost (1984) showed that fire regimes can be schematically represented as particular combinations of fire frequency, intensity and seasonality (Figure 7). However, all combinations are not equally likely to occur in nature. Therefore, nowadays, except for National Parks and reserves where the managed fire regime tends to emulate natural fire regime, the majority of African savannas and forests present anthropogenically dominated fire regimes. The major components of the fire regime for each type of the vegetation in the southern hemisphere of the African continent (i.e. from deciduous forest to savannas and grasslands) have been summarized by van Wilgen and Scholes (1997) and are reported and completed in Table 1.

Figure 6. Fire spreading in a semi-arid Namibian savanna with open canopy layer and "sweet grasses".

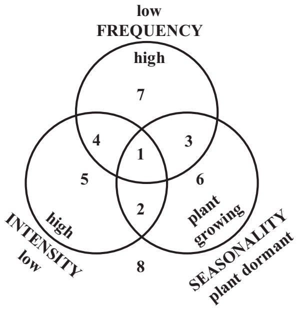

Figure 7. Diagram illustrating possible combinations of fire frequency, intensity and seasonality giving rise to different fire regimes (from Frost, (1984)). Regimes numbered in approximate order of severity to the organisms. Not all combinations are equally likely to occur in nature. Within the South African region, combination 2 probably applies to forest, 7 (or possibly 4) to moist savannas and grasslands, and 8 to arid grass and shrublands.

Table 1. Components of the current fire regimes for African savannas and related vegetation type in. Kruger National Park (KNP) and, Etosha national Park (ENP).

Vegetation type	*Fire type and season*	*Fire frequency*	*Fire behaviour*	*Sources*
Dry/deciduous forests	Surface or crown fires. Dry winter season generally June to September.	20-100 yr intervals	Variable. Fire intensity typically low if only litter is consumed, can be very high if stem wood ignite	No fire-related literature exists (van Wilgen and Scholes 1997)
Moist infertile savannas	Surface fires in grass layers. Restricted to dry winter when grasses cured and dormant. Trees may be scorched but low flammable tree foliage. Frequent back fires.	1-6 yr intervals (mean of 2-3 yr in KNP).	Intensities <100 to 6000 kW/m. Back fires more intense. Woody species more affected by head fires as heat energy release occurs at levels near terminal buds	(Trollope 1984b, Frost et al. 1985, Trollope and Potgieter 1985, Trollope 1993, van Wilgen and Scholes 1997)
Arid fertile savannas	Surface fires in grass layers. Restricted to dry winter when grasses cured and dormant Frequent back fires.	2-11 yr intervals (mean of 4-8 yr in KNP, 3-10 yr in ENP). Lightning ignition dominates in National Parks	Intensities <100 to 4000 kW/m. Lower than in moist savannas due to lower fuel load	(Siegfried 1981, Trollope 1984b, Frost et al. 1985, 1993, van Wilgen and Scholes 1997)
Infertile grasslands	Surface fire only. Restricted to dry winter.	2-4 yr intervals. Annual fires are possible (mean of 3 yr in the natal Drakensberg, South Africa).	Intensities: 1000 -3000 kW/m	(van Wilgen et al. 1990, van Wilgen and Scholes 1997)
Fertile grasslands	Surface fire only. Restricted to dry winter.	4-10 yr intervals, with the lower frequencies in the more arid areas.	No data	No fire-related literature exists (van Wilgen and Scholes 1997)

5.2 SOUTHERN AMERICAN CERRADO

Cerrado comprises several physiognomic forms, which constitute a biological gradient: grasslands (campo limpo), open shrub savanna (campo sujo), woody savannas (cerradao), and dry deciduous forests (riparian forests) (Santos et al. 2003). Cerrado sustains surface fires all over the landscape mosaic, but the fire frequency varies according to the openness of the stands (Coutihno 1990, Pivello and Coutihno 1996). For instance, fire is naturally infrequent in closed canopy dry forests and occurs only during abnormally low rainfall years, or if ignited by human activities such as those currently related to deforestation (Uhl and Kauffman 1990, Nepstad et al. 1997, Cavelier et al. 1998, Cochrane et al. 1999). In such cases, the fire only consumes the litter and grass layers, but because of the typically thin tree bark, it still kills roughly 95% of the stems (invested by the fire) larger than 1 cm in diameter at breast height. Only large, thicker barked trees survive. By exposing the mineral soil, the ground surface temperature increases, and the soil dries out, inducing further stress in the surviving individuals. After the fire, combustible fuels of all sizes fall from standing dead trees and tree mortality continues for at least 2 years. Thus, this first fire changes the forest functioning and increases the forest susceptibility to burn in the near future (Cochrane et al. 1999). The opening of the canopy (50 to 70% cover) allows greater solar heating and air movement to dry out the forest fuels. Successive fires change forest composition from non-tolerant fire species to more tolerant ones. They also slowly open the forest canopy by killing trees and favouring grass growth (Cochrane and Schulze 1998), transforming the forest into a savanna stand even more susceptible to frequent fires with higher intensities (Cochrane and Schulze 1999). Grasslands are the most open stands and present the highest fire frequencies from 1 to 3 years (San Jose and Farinas 1983, Sanaiotti and Magnusson 1995). The "bush encroachment" phenomenon occurs also in cerrados (San Jose and Farinas 1983, Moreira 2000). Such shifts from forest to savannas and grasslands and the reverse occurred several times in the past (i.e., back to the Pleistocene and Holocene) as a result of climate change (Kellman 1975, Meave and Kellman 1994, Desjardins et al. 1996, Cavelier et al. 1998). In such shifts, riparian forest may have played an important transitional stage with a high tree species diversity and relatively small individuals as a result of frequent disturbances such as fires (Meave and Kellman 1994). Nowadays, this shift from forest towards grassland results mainly from human activities superimposed to the current climate change conditions (Uhl and Kauffman 1990, Nepstad et al. 1997, Cavelier et al. 1998). The unknown effects depend on the speed of this change as several species may be unable to adapt their resistance against fire and could disappear in the near future (Kauffman et al. 1993, Nepstad et al. 1997, Nepstad et al. 2001). To illustrate the impact of land use management on current fire regime in the Brazilian cerrado from the State of Parà, Cochrane and Schulze (1998) estimated that over the next 25 years 90 % of the currently unburned areas will be impacted by fires at least three times (Figure 8). The disappearance of unburned areas will be likely associated with the extinction of several species in these ecosystems (Cochrane and Schulze 1998). The different components of fire regimes in cerrado mosaics have been compiled from literature review and are presented in Table 2.

Table 2. Components of the current fire regimes for South American cerrado and related vegetation types.

Vegetation type	*Fire type and season*	*Fire frequency*	*Fire behaviour*	*Sources*
Amazonian Rain forest (riparian forest)	Surface to crown fires. Naturally during extreme droughts.	Past: 20-100 yr intervals. Currently 40-60 yr in Belize and Venezuela. Mainly due to deforestation with associated dryness of microclimate.	Variable. Fire intensity typically very low as only litter consumed during the first fire. Increasing intensity during successive facilitated burns.	(Uhl and Kauffman 1990, Kellman and Tackaberry 1993, Kellman and Meave 1997)
Cerradao (medium - tall woodlands with closed canopy dry/deciduous forests) *Cerrado (savanna woodlands of low trees or shrubs)*	Surface fires in grass layers. Canopies of trees scorched but do not contribute to combustion. Large fires during dry winter season (May to September, maximum in August). Lightning fires frequent during wet season creating small burned areas.	50-60 yr intervals down to 3-4 yr for severe fires in Emas National Park and Chapada dos Veadeiros National Park (Brazil).	No fire-related literature exists.	(Coutihno 1990, Kellman and Meave 1997, Ramos-Neto and Pivello 2000)
Campo sujo – open savanna with scattered trees or shrubs	Surface fires with high fire activity induced by lightning in Belize. Dry winter season.	1- 10 years with mean interval of 2-3 yr when used as pasture management.	Low intensities probably like in African fertile arid savannas (<100 to 4000 kW/m).	(Kellman 1975, Coutihno 1990)
Campo limpo - Grasslands	Surface fire only.	1-3 yr intervals. Frequent annual fires.		(Uhl and Kauffman 1990)

5.3 MEDITERRANEAN VEGETATION

The garrigue ecosystem has been present in the European Mediterranean region since the last glaciation (Carcaillet et al. 1997, Carrion et al. 1999, Willcox 1999, Brewer et al. 2002). It results from the successive fires that burned the widespread forests of Oaks (*Quercus ilex, Q. suber,* and *Q. coccifera*) and Pines (*Pinus halepensis*). Garrigue was originally featured from natural wildfires, and then mainly related to intensive human activities starting 7 000 years BP for agricultural and pastoral purposes (Trabaud et al. 1993). A new wave of intensification in the fire use started with the beginning of the historical period (750 BC until today). Today, lightning fires represent only about 2% of the area burned annually in the Mediterranean Basin (0-6%, depending on the country (Trabaud et al. 1993)). Fire ignition sources are therefore mainly accidental or voluntary activities as compared to lightning, and these human fire ignitions are responsible for the high number of small fires as compared to past periods (Lloret and Mari 2001). Essential oils and waxes are representative chemical components found on different but common species such as thymus (*Thymus vulgaris*), rosmarinus (*Rosmarinus officinalis*), and pines. Moreover, sclerophyll leaves and needles, which have been first selected for drought resistance, reinforce the fire hazard and fire propagation over wide areas during summer when very dry and hot air masses associated with strong winds dominate the region. Less than a century ago, the garrigue was used and managed on a yearly basis to feed goats and sheeps from spring to fall.

Vegetation removal by animals was reducing both the fuel load and the fire hazard associated with breaking the continuum in spatial arrangement of fuel. In the second half of 20th century, agricultural practices have shifted and such land management has disappeared. The main direct effect of such abandon has been the fuel load accumulation from the ground surface to the shrub and small tree crowns, inducing an overall average fire frequency of 15 to 20 years. However, several stages of vegetation can be distinguished based on the composition and the structure of the vegetation inducing different fire regimes (see Table 3 for details). All these vegetation types present the same fire season from late spring (June) to early fall (September) based on the Mediterranean dry period climate. Several studies have shown that all these vegetation types present the particular pattern of post-fire regeneration known as "autosuccession" where post-fire vegetation composition is generally the same as the pre-fire composition (Odion and Davis 2000). This is explained by the fact that vegetation is maintained by fire resistant species (*Quercus suber* and its very thick bark of cork), fire-induced seed germination (*Pinus halepensis* and its serotinous cones), obligate postfire shrub seedling regeneration, and resprouting from geophytes and fire resistant ligotubers (*Q. coccifera Q. suber*, and *Q. ilex*, *Pistacia lentiscus*) (Trabaud 1989). *Quercus coccifera* garrigue is subject to frequent burns preventing other tree species to settle and therefore fire in such case is recognized as a blocking succession disturbance. If fire interval increases, the succession will succeed to start again and the forest stage will succeed to the *Q. coccifera* shrubland stage. In forested stages, oaks stand succeed to pines. In pine forests, if fire intervals are shorter than the time necessary for pines to produce fertile cones then the postfire stage will go back to a Garrigue stage.

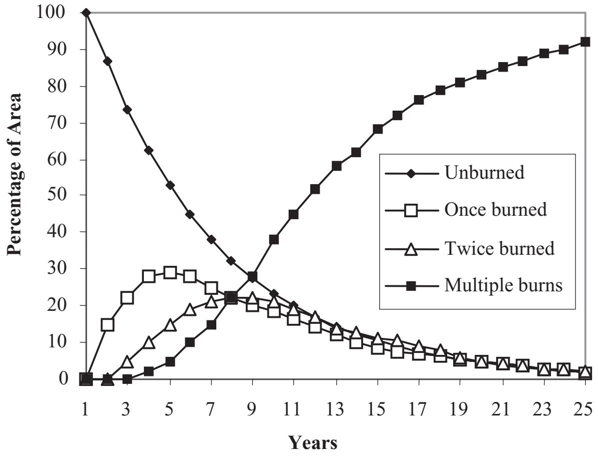

Figure 8. Projected 25-year change in forest type near Tailândia, Parà (Brazil), under the current fire regime. Unburned forests are present within the fire affected matrix. The multiple burns class lumps together all forests burned three or more times (From Cochrane and Schulze (1998)).

Table 3. Components of the current fire regimes for Mediterranean garrigue and related vegetation types.

Vegetation type	*Fire type and season*	*Fire frequency*	*Fire behaviour*	*Sources*
Garrigue	"Crown" fires in the unique shrub layer; Dry summer season from late spring (June) to early fall (September).	5-7 yr intervals down to 2-3 yr in *Q. coccifera* garrigue.	Intensity: variable (low intensity in early spring fires and very intense later), only qualitative assessment of intensity related to temperature rather than to energy release.	(Rego et al. 1993, Trabaud et al. 1993)
Maquis	"Crown" fires in the unique shrub layer; Dry summer season.	10-20 yr intervals, up to 40 yr in Californian chaparral.	Intensity: variable (low intensity in early spring fires and very intense later), only qualitative assessment of intensity.	(Trabaud et al. 1993, Odion and Davis 2000, Mouillot et al. 2002)
Coniferous forest (Pinus sp.)	Surface and crown fires depending on meteorological conditions (strong wind). Dry summer season.	30-70 yr intervals.	Intensities: up to 15 000 kW/m with strong wind and drought.	(Trabaud 1989, Trabaud et al. 1993, Lloret and Mari 2001, Mouillot et al. 2002)
Deciduous forest (Quercus sp.)	Surface and crown fires depending on meteorology (strong wind). Dry summer season	30-50 yr intervals down to 5-25 yr in *Q. suber* and *Q. ilex* forests.	Intensities: up to 15 000 kW/m with strong wind and drought.	(Trabaud et al. 1993, Trabaud and Galtié 1996)

6. Conclusion

Fire regimes of dryland systems are highly influenced by the water components. Indeed, it has been shown that dryland fuels are directly related to climate through precipitation for the fuel production and relative humidity and moisture content for fuel flammability. The driest lands, receiving sparse and scarce rainfall, present longer fire returns due to slower rates of fuel production and accumulation than moister lands. The fire event retroactively influences the hydrology. Indeed, the vegetation removal decreases the interception and the evapotranspiration, whereas it increases the surface runoff. Indirectly, fire can also influence the erosion processes. These physical changes are associated to chemistry modification. Indeed, during the fire event nutrients stocked in vegetation are released in the atmosphere and on the ground. Therefore successive frequent fires may irreversibly change the biogeochemistry of soil and water reservoirs.

Dryland systems are in general dominated by grass and shrub layers, sustaining surface fires with low intensity and variable rate of spread, and producing few amounts of ashes and charcoals as compared to denser tree canopies. Therefore, fire events in dryland systems leave short lasting scars that need to be detected quickly after the fire has occurred in order to properly estimate fire regime components. Remote sensing technology is efficient for such task but needs better spatial and temporal cover and resolution.

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