Wildfires, Weather, and Productivity

Michel Louis Bernard[1] and Noureddine Nimour[1]

Abstract—The object of this paper is to show the intercorrelations existing between statistics of wildfires (occurrences: N; areas burned: A), climatic parameters (precipitation: P; temperature: T) and net primary productivity: NPP. To this purpose, statistics of wildfires have been studied in several regions of the world, focusing on temperature and precipitation. The present analysis has been performed on French Mediterranean Departments (Bouches-du-Rhône, Hérault, and Var), Northern Ontario (Canada), Alicante Region (Spain), Yellowstone National Park –YNP-(USA), San Diego (California, USA). Concerning the temperature, the monthly analysis of fire occurrence shows two distinct periods with different fire production laws, both being of the Arrhenius type: the first one corresponding to the vegetation during the rest period, the second one during the vegetative production period. Concerning the precipitation, the monthly analysis of fire occurrence led to two distinct laws depending on the region climatic type (or eventually the seasonal characteristics). Thus, the monthly variation of fire occurrence (in log scale) is a linear increasing or decreasing function according to precipitation. In French Mediterranean Regions these expressions are bound to the rate of soil water extraction by the plant roots (a limiting step of plant production?). Out of the intrinsic importance of the presented results, in the field of primary productivity (dependence on Kelvin temperature) it brings a confirmation of the reality of our hypothesis on the role of the limiting steps of plant production in the rate of wildfire production.

Introduction

Wildland fire studies on a statistical point of view are more fructuous in information than the individual determinist studies. They are the only ones allowing correlating wildland fires with intrinsic factors (nature and composition of vegetation, water content...) or extrinsic factors (precipitation, air temperature, wind, lightning...) given an area and period of time. In the first part of this document, we will discuss our studies of the dependence of fires occurrence and burnt area on meteorological data (precipitation and temperature).We will then show how correlations obtained can be representative of climate of some regions. That will finally lead us to show you how they are bound to vegetation productivity on an annual scale.

Wildfire and Climatic Parameters

Statistics of wildfires have been studied in several regions of the world, focusing on temperature and precipitation. The present analysis has been performed on French Mediterranean Departments (Bouches-du-Rhône, Hérault, and Var), Northern Ontario (Canada), Alicante Region (Spain), Yellowstone National Park –YNP-(USA), San Diego (California, USA).

Wildfires and Precipitation

Past works—Many works have been done on the influence of water content of plants on their flammability and the propagation of wildland fires. On the contrary, only a few thorough studies have been published on the role of precipitation on wildland fires.

Trabaud (1980) has studied occurrence of fires of *Brachypodium Ramosum* in the Montpelier garrigue. According to him, rainfall is the more important climatic factor that influences occurrence of fire. It is not really the total quantity of rainfall that is a stopping event, but rather its distribution mode. According to him, the number of fires is an exponentially decreasing function of precipitation. However, the statistical curve he showed expresses a $1/X$ function, not an e^{-x} function.

Trabaud has looked for predictions of fire occurrence taking account of rainfall regime, and particularly of the number of days without rain that increases risk of fires. He proposed a model that has shown that the risks of fire increase linearly as dry periods are longer.

Douguedroit (1992) pointed out the close relation between precipitation and wildland fires in the Mediterranean region. Precipitation in summer controls actual evapo-transpiration (AET) but no correlation analysis between these factors is proposed.

Latham and Rothermel (1993) have investigated the possibility that a useful probability of fire stopping precipitation could be developed from historical weather records. Persons familiar with weather and fire behavior suggested a fire stopping precipitation criterion of "at least 0.5 inches of precipitation in 5 days or less." Using data from weather stations in the Northern Rocky Mountains, USA (daily precipitation data for the period between 1970 and 1985) they found that the Weibull probability distribution was an excellent fit for the problem. The method can be applied to other "*fire stopping criteria*" using the same techniques.

Viegas and Viegas (1994) have related the total area burned yearly in Portugal (from 1975 to 1992) to rainfall during particular periods of the year. The best correlation: annual burned area – precipitation, concerns the modified precipitation observed in Coïmbra from June to September of each year, showing that it is possible to use data from a single weather station to represent rainfall in a wider area.

Forgeard (1994) has related the monthly number of fires in the Lande Bretonne (west of France) to precipitations for the years 1976 to 1993. Their number (Y) is correlated to monthly precipitation (X) according to the equation:

$$Y = 98.968 + 1.7885 \ X \ (R^2 = 0{,}781)$$

Daily correlations: lightning fires in Northwestern Ontario—Wildland fires may have different possible causes, most of them being human causes. To avoid any influences coming from various causes we have taken account in a preliminary study only a natural cause: lightning ignited fires.

A number of Canadian fires are lightning ignited fires: according to Boulard (1993) they represent a proportion of 30 to 50 percent of fires.

Flannigan and Wotton (1990) have investigated the relationship between lightning activity and the occurrence of lightning-ignited forest fires in the Northwestern region of Ontario. They found that Duff Moisture Code and the multiplicity of the negative lightning discharges were the most important variables for estimating the number of lightning ignited fires. Fires have been counted with corresponding values of local precipitation and temperature. From

data files provided by the authors and completed by the Ontario Ministry of Natural Resources (Ward 1994), we have analyzed the data relating to UTM:15 zone, to be 1,152 fires accounted in 1988.

In this region, in a log scale (fig. 1), the variation of fire occurrence is a linear increasing or decreasing function of precipitation. The distinction between the two regimes has been done comparing temperature periods:

$$\text{Log } N = 1.019 + 0.0622P \qquad \textit{For humid and warm period}$$
$$\rightarrow \qquad N = 10.44 \text{ e}^{+0.143P}$$
$$\text{Log } N = 2.739 + 0.2517P \qquad \textit{For dry and cold period}$$
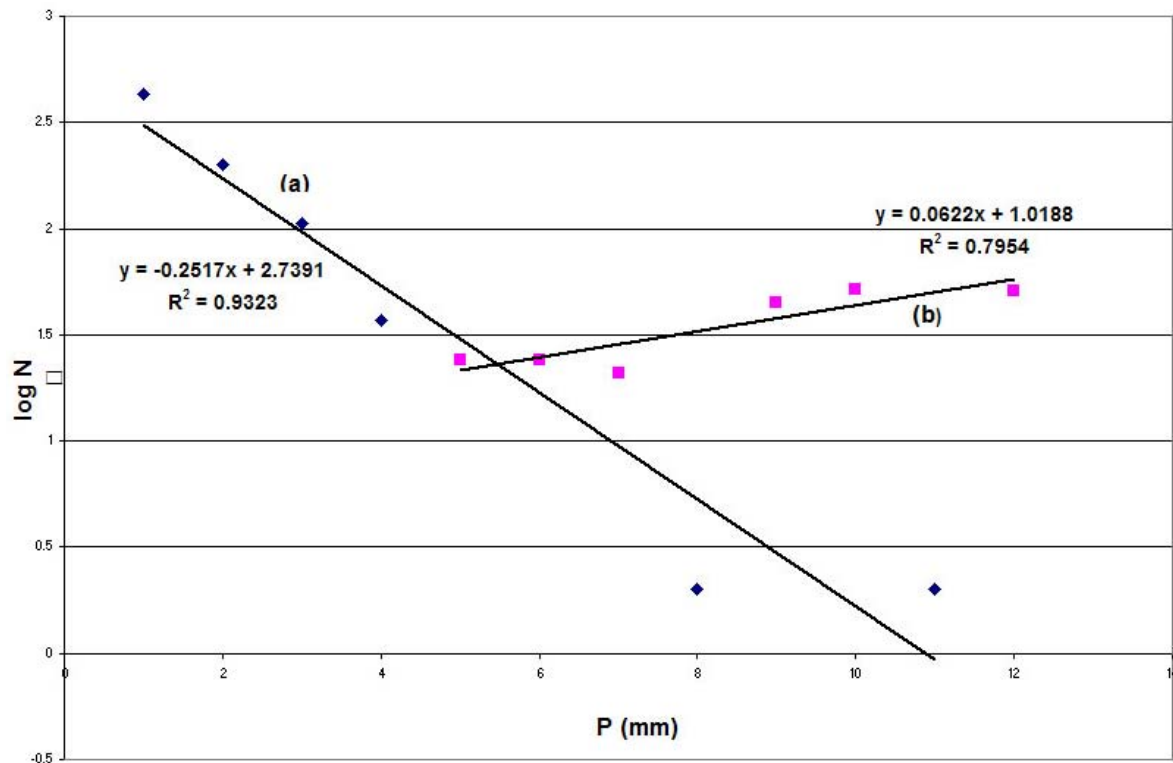$$\rightarrow \qquad N = 548 \text{ e}^{-0.579P}$$

Figure 1—Log N = g(P). Ontario, UTM15, 1988.

Humid period for precipitation must be associated to warm period for temperature. So precipitation highly contributes the evapo-transpiration during this period (positive exponent). Dry period for precipitation must be associated to cold period for temperature. So precipitation contributes to evapo-transpiration at a low rate.

The humid and warm periods approximately correspond to the periods of vegetation production in this region (sub artic region).

Daily correlations: wildfires in West Var (1973)—Olivier (1975) has studied the role of vegetation and ecological factors on the "Basse Provence" region wildfires. Individual wildfires were registered from area as low as 0.01 ha over the whole year 1973.

Occurrence of fires and precipitations were summarized by half a month values (fig. 2). Again we observe the same type of behavior:

(1) Log N = 0.6306 + 0.0107 P   *For humid and cold period*
(2) Log N = 1.1716 + 0.0125 P   *For dry and warm period*

The warm and dry period approximately corresponds to the period of vegetation production in this region (Mediterranean region).

Such typical relations have been found in other Mediterranean regions such as:

- Languedoc-Roussillon region (data from Rambal 1984):

(3)   Log N = 2.8961 – 0.0047P

- Alicante region (data from Terol 1987):

(4)   Log N = 1.537 – 0.029P

So the monthly occurrence of fires in Mediterranean regions in the warm period is a function of the exponential form:
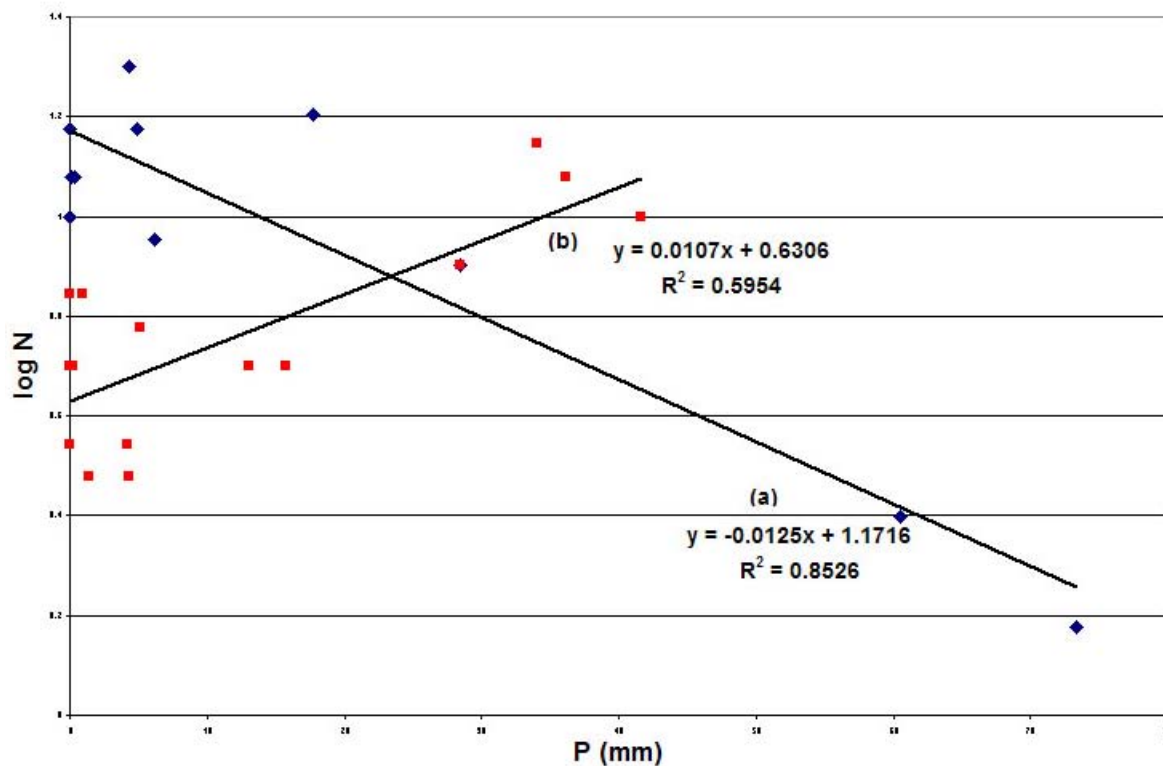
$$N = Constant * e^{-\alpha P}$$

Figure 2—Log N = g(P). West Var, 1973.

In order to interpret these equations, it is necessary to examine the dynamics of water in the ecosystem, that is to say, soil water balance and the relative importance of its different terms with season (particularly during the summer season, in the Mediterranean regions; Humbert and Najjar 1992).

Rambal (1984) has studied soil water balance and water uptake characteristics by *Quercus Coccifera L*, which cover in the **garrigue more than** 100,000 ha in the French Mediterranean region.

Water balance equation: $\Delta S = P * R * AET * D$

Where ΔS is the daily change in stored water, P is the precipitation, R is the surface runoff, AET is the actual evapo-transpiration and D is the flow of water at the bottom of the root zone measured in mm/day.

The study of water balance during every year shows that when yearly precipitations are less than 578 mm, deep drainage loss is negligible and almost all the precipitations infiltrating the soil are lost by evapo-transpiration. Studying the water uptake at different deepness in the summer, Rambal proposed a relation between the relative deep uptake and the precipitation. According to Rambal, precipitation modifies relative water uptake Y (%) according to an exponential law:

$$Y = 25.7 * e^{-0.006 * x} \qquad r^2 = 0.963$$

X being precipitation in June and July.

This relative water uptake is also the expression of relative actual evapo-transpiration, which is the equivalent of photosynthetic fixation of carbon within the same period (Frontier and Viale 1991; Ramade 1994). Photosynthetic activity on plants leads to formation of new twigs and chemical modifications of old ones, then to production of fire sensible biomass.

Interannual occurrence of fires in Var area—Yearly occurrences of fires have been correlated to precipitation with the data of Var area, for the period 1974 to 1986 (Promethee Databank). Several 1-year periods have been tested, and the best result was found taking a period starting in July. The correlation equation is:

$$\text{Log } N_{annual} = 2.90 - 0.000365 P_{annual} \qquad \text{with } r^2 = 0.98$$

Thus, we can conclude that in Mediterranean regions, during the vegetation production period, occurrences of wildfires (monthly or yearly) are regulated by the deep water uptake rate of plant roots.

Wildfires and Temperatures

Quantitative effects of temperature on wildfire statistics have not been developed as for precipitation. In order to approach the problem we appealed to chemical kinetics laws.

Considering the parameters of fire occurrence N or area burnt A, during a defined time interval and in a given region as reaction rates in chemical kinetics, we studied their possible dependences to Arrhenius factor E/RT, E being the activation energy of the reaction, R the gas constant, and T Kelvin temperature (compare: lightning fires dependence on precipitation and temperature, Bernard 2004c).

Lightning fires in Northwestern Ontario—Coming again to Northwestern fire data (fig. 3), we observe two Arrhenius plots, the first being the warmest period and the second the coldest one. During the vegetation production period (warmest period) the activation energy corresponds to photosynthesis. During the vegetation rest period (coldest) the activation energy corresponds to U.V.B. energy.
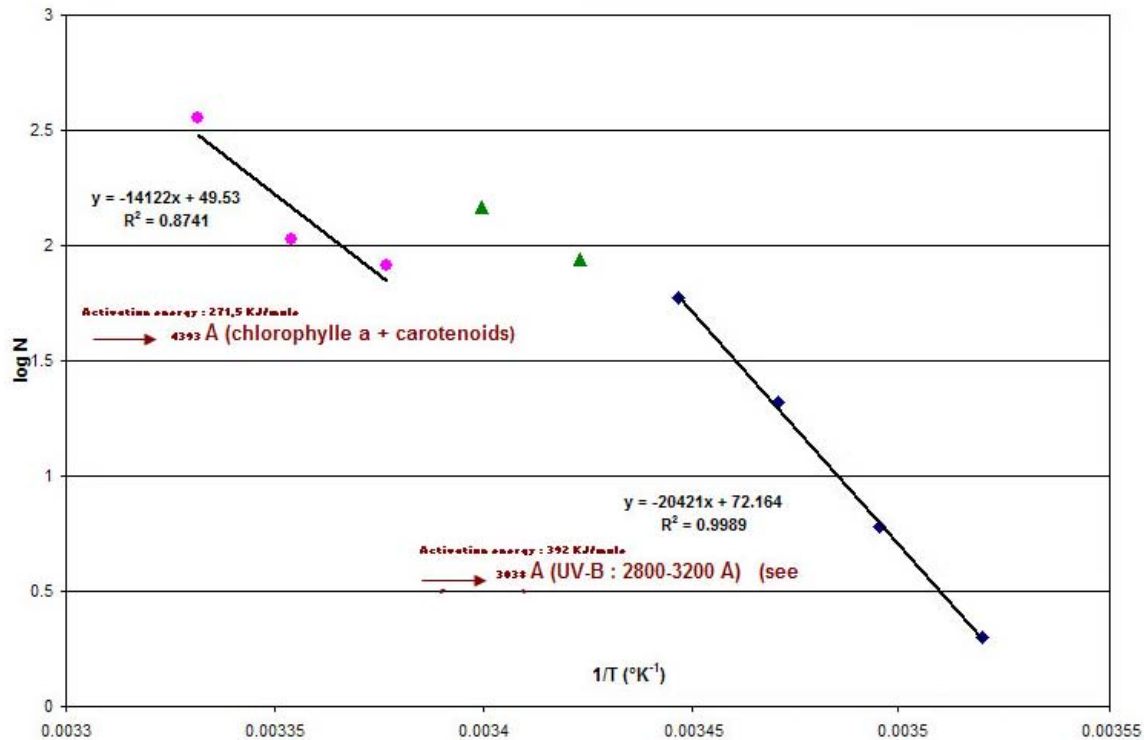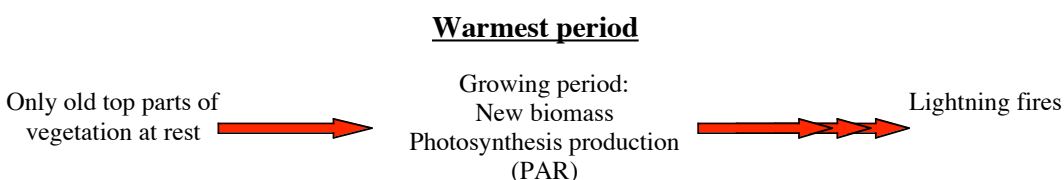

Figure 3—Log N = f(T). Ontario, UMT 15, 1988.

Log N = 49.52 – 14,122 / T   →   **Warmest period**
E_{act} = 271.5 KJ/mol.   →   439.3 nm (Chlorophyll A)

Log N = 72.164 – 20421 / T   →   **Coldest period**
E_{act} = 392 KJ/mol.   →   303.8 nm (U.V.B)

In analogy with the chemical kinetics laws, to interpret those results, we need to use the law of the bottleneck (the rate of the global reaction is determined by the slowest rate among the different successive reactions that compose it).

<u>**Warmest period**</u>

Only old top parts of vegetation at rest ➡ Growing period: New biomass Photosynthesis production (PAR) ⇒⇒ Lightning fires

Rate of global processes (N) controlled by rate of the biomass production

Coldest period

Vegetation at rest
(before or after   ➡   Lightning fires
growing period)

Rate of global processes (N) controlled by U.V. flux

Wildfires in Bouches-du-Rhône area 1986—Two Arrhenius linear plots are observed for monthly wildfire in Bouches-du-Rhône area (fig. 4) with a good square correlation coefficient (**$R^2 = 0.93$**), one for the summer period and another for the winter period. These results must be interpreted using the same argument as for the wildfires in Northwestern Ontario.

Other equations of Arrhenius type have been observed for Mediterranean type regions:

- Languedoc-Roussillon area (temperature in Montpellier)

$\text{Log } N = -5797 * 1 / T + 22.034$ $(R^2 = 0.461)$

- Southern California, USA, 2005 (temperature in San Diego)

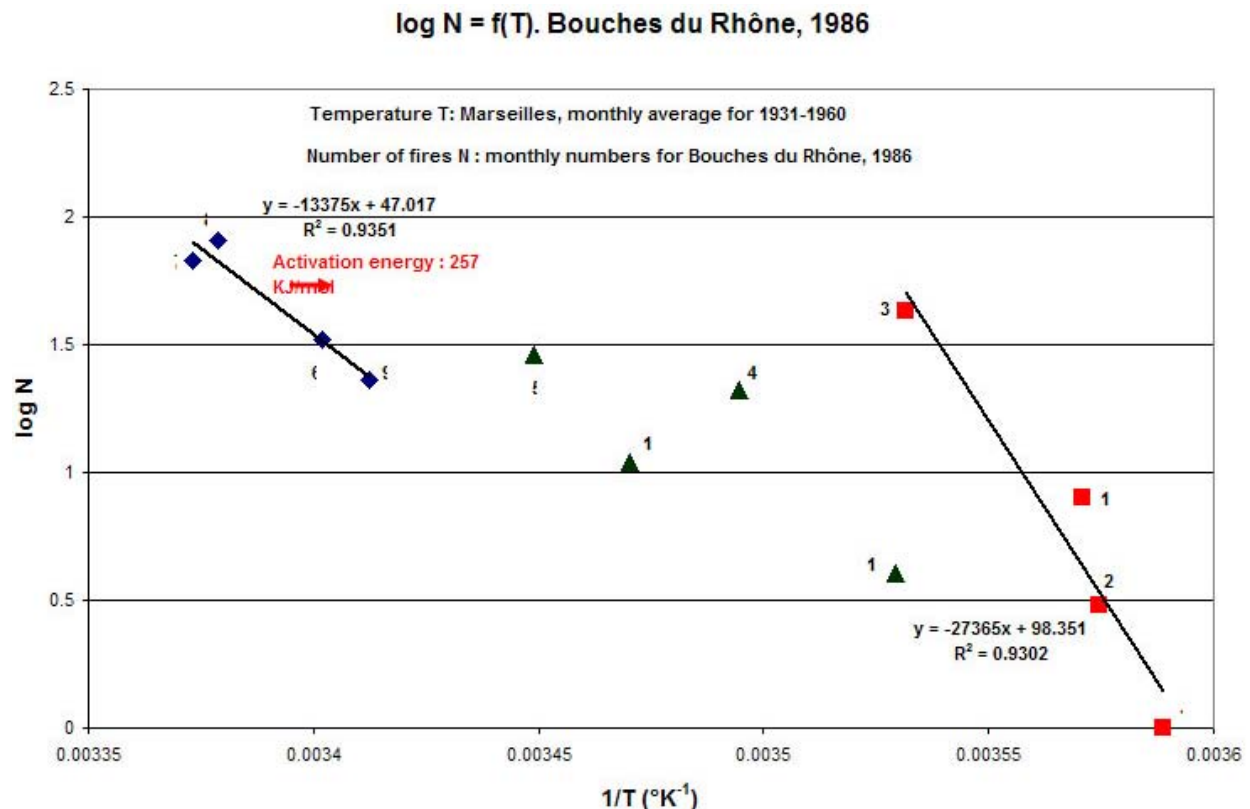$\text{Log } N = -28674 * 1 / T + 99.04$ $(R^2 = 0.497)$

Figure 4—Log N = f(T). Bouches-du-Rhône, 1986.

Annual Wildfires in Yellowstone National Park—They have been extensively analysed as much on area burnt as on wildfire occurrences, and as much on lightning caused fire as on human ones (Douglas 1975; Romme 1989; Despain 1998). See Bernard (1998a): interpretation of fire intensity in Yellowstone National Park for the 1700-1990 period.

Most of the wildfires in YNP are class 3 fires (fig. 5). We observe the same Arrhenius law with the lightning fires (fig. 6) on the annual occurrence criterion.

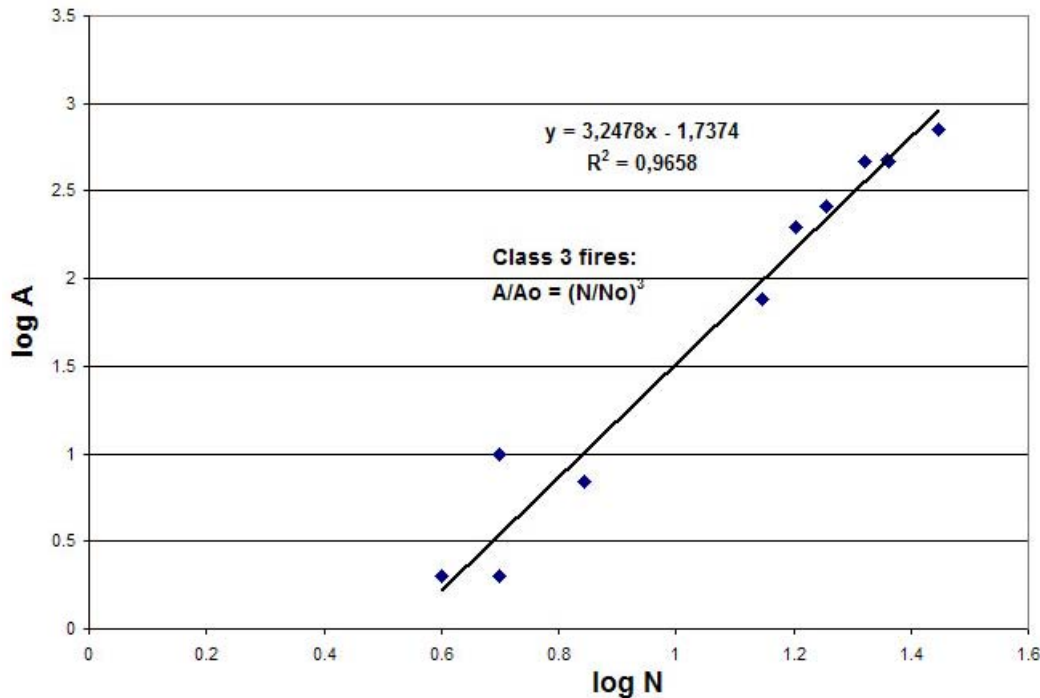**Figure 5**—Yellowstone National Park: log A =f(log N). Human caused fires. Years: 1933, 1934, 1940, 1947, 1948, 1949, 1953, 1954, 1955, 1960, 1967, 1968.
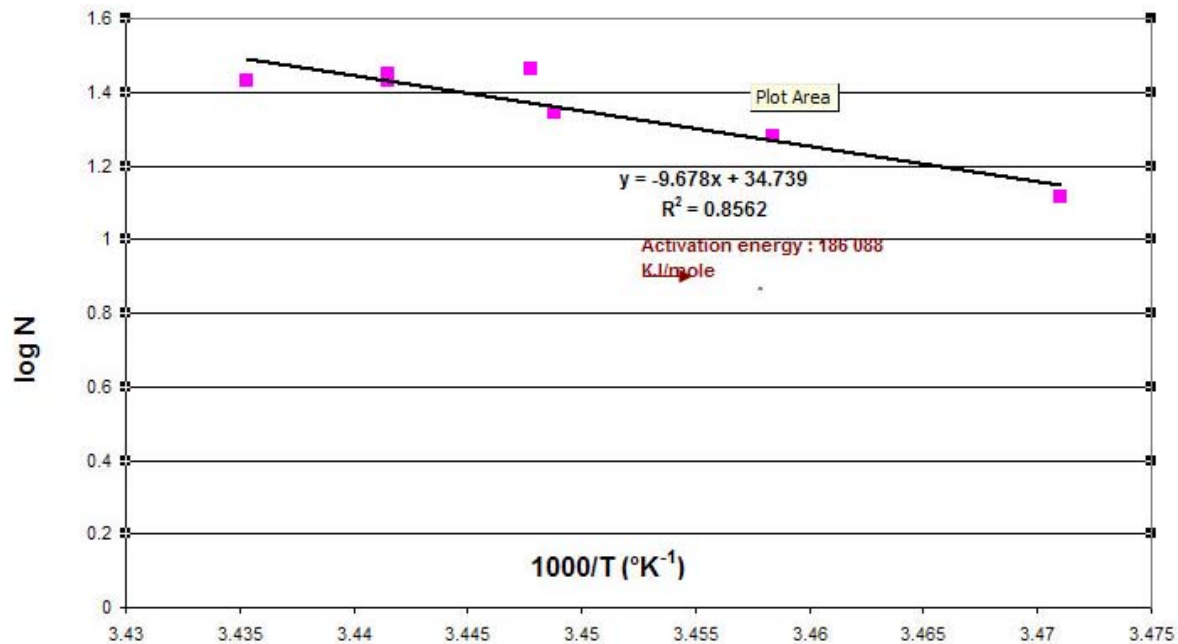

Figure 6—Yellowstone National Park: logN= f(T) Lightning fires. Years: 1933, 1948, 1949, 1952, 1960, 1961, 1963.

For the human caused fires, the Arrhenius law is verified for both annual occurrences and area burnt criterion (fig. 7).

Thus, we can conclude that the rate of photosynthetic radiations regulates the monthly occurrence of fires during the vegetation production period and yearly occurrences of fires and area burnt at the interannual scale.
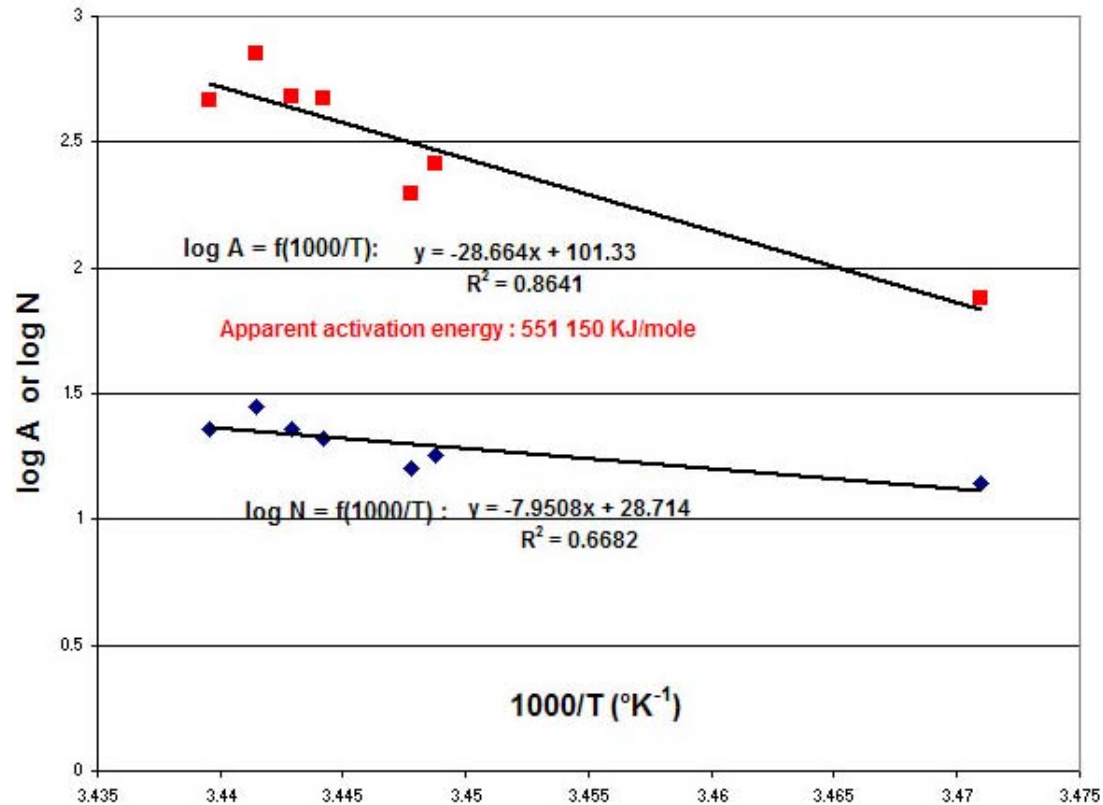

Figure 7—Yellowstone National Park: log A = f(T) and log N = f(T). Human caused fires. Years : 1933, 1934, 1940, 1948, 1949, 1953, 1960.

Wildfire and Climate

During the vegetation period we define the occurrence of fires as function of variable P and T.

$$(1) \quad \text{Log } N = a + b * P$$
$$(2) \quad \text{Log } N = c - d / T$$

We observe the following conditions on the constants:

- c : c > 0,
- d : d > 0,
- a : a > 0,
- b : b > 0   (NW Ontario Climate)
        b < 0   (Mediterranean type Climate)

In the equation 1, N is univocal of P, in equation 2, N is univocal of T. P and T are measured data or data taken from meteorological stations and are interdependant in the vegetation production period.

Identifying the two equations, we get:

$$(3) \quad P = (c-a) / b + d / (b *T)$$

We now need to compare this relation (3) to real temperature and precipitation data of different regions.

Wildfires in Northwestern Ontario

Referring to the figure 1 for precipitation and figure 3 for the temperature, here are the equations expressed with the real data from Northwestern Ontario:

$$(1') \quad \text{Log } N = 1.019 + 0.0622P$$
$$(2') \quad \text{Log } N = 49.5 - 14{,}122 / T$$

By identification, we get:

$$(3') \quad P = 780 + 0.227 *10^6 / T$$

To compare those data, we choose the 1988 meteorological data from Sioux Lookout station in Ontario, and try to demonstrate this relation monthly from May to August 1988. Figure 8 shows what we found for each studied month. We found an equation that even has a **correlation coefficient equal to 1**:

$$P = 3{,}607 - 1.044* 10^6 / T \qquad (R^2 = 1)$$

We observe:

- Climate data from Sioux Lookout verify the linear correlation P, 1/T.
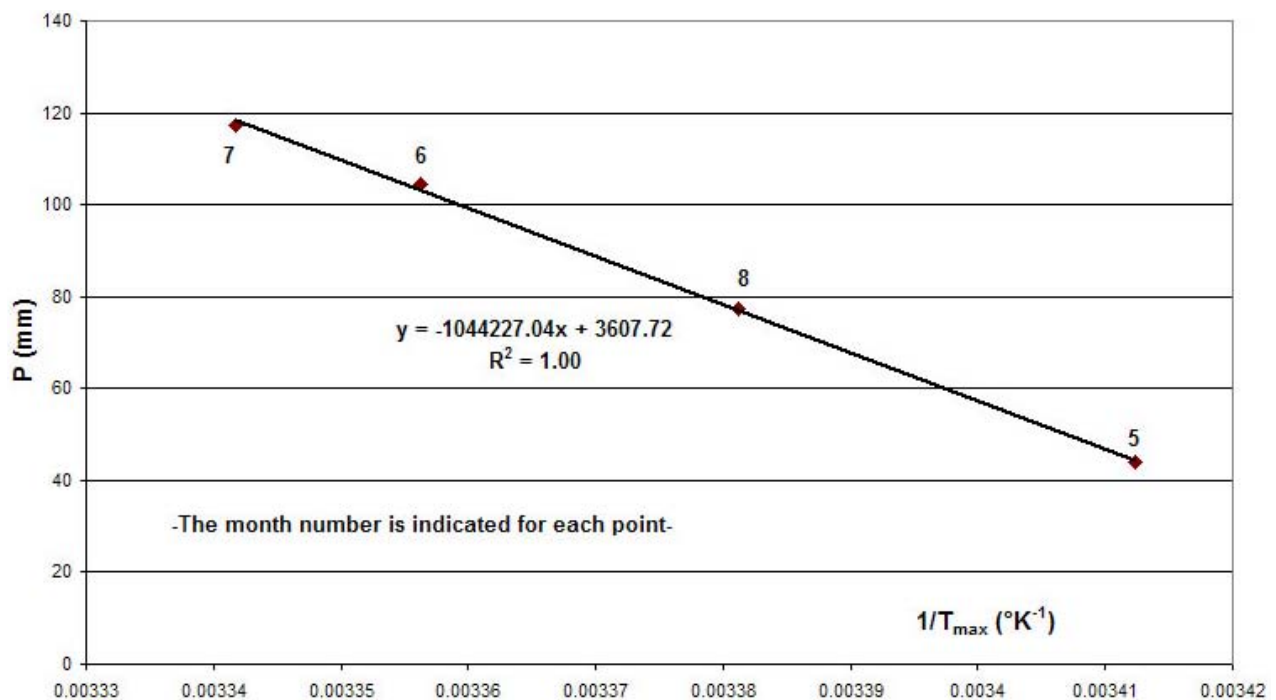- Precipitation from Sioux Lookout is found 4.6 times larger than from the N.W. Ontario region.

Figure 8—Climatologic chart of Ontario, UTM 15, Canada at Sioux Lookout meteorological station. P = f(Tmax). May-August 1988.

Wildfires in the Languedoc-Roussillon Area

The next equations (1") and (2") are explained in a deeper way in a former publication (compare "Application of the concept of climatologic chart to Mediterranean climate variability," Bernard and Nimour 2005a).

Here are the equations expressed with the real data from Promethee database and from Rambal (1984). For Montpellier, we found:

$$(1")\quad \text{Log } N = 2.896 - 0.0047\, P$$
$$(2")\quad \text{Log } N = 22.034 + 5{,}797\, /T$$

By identification, we get:

$$(3')\quad P = -4{,}071.91 + 1.234 *10^6 / T$$

To compare those data, we choose the average values of meteorological data from Montpellier station in Languedoc-Roussillon (the average values of each month are calculated over the 1964 to 1982 period for precipitation, and the 1980 to 1982 period for temperatures). We try to demonstrate this relation monthly from July to October. Figure 9 shows what we found for each studied month. We found an equation that even has a **correlation coefficient equal to 0.9995**:

$$P = -3{,}932.7 + 1.00* 10^6 / T \qquad (\mathbf{R^2 = 0.9995})$$

The agreement is very satisfactory: Climate data from Montpelier verify the linear correlation P, 1/T
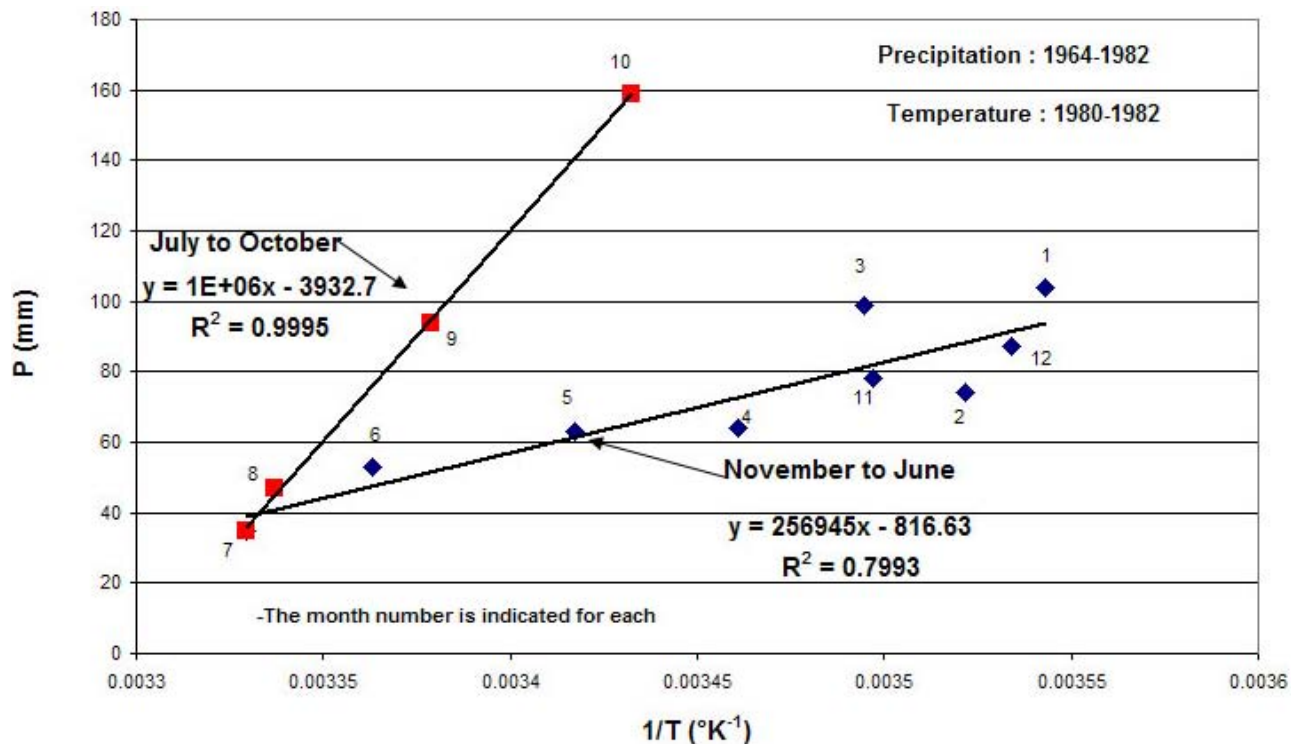

Figure 9—Climatologic chart of Montpellier.

A Concept of Climatologic Chart

Other reconstructions of climate from wildfire occurrence have been stated. That confirms the generality of the method. So we introduced the concept of climatologic chart ("A concept of climatologic chart," Bernard and Nimour 2004a), which is based on the law of interaction between the vegetation, the soil, the water, the atmosphere, and the solar radiations.

Climatologic charts could be more useful than historic representations of climate characteristics (climatogram, Emberger or Gaussen ombrothermal diagrams) to build a new classification of climate in order to perceive any possible climate changes (compare "Application of the concept of climatologic chart to Mediterranean climate variability," Bernard and Nimour 2005a).

To illustrate the prior statement, we can refer to figure 10 as an example of semiarid climate.
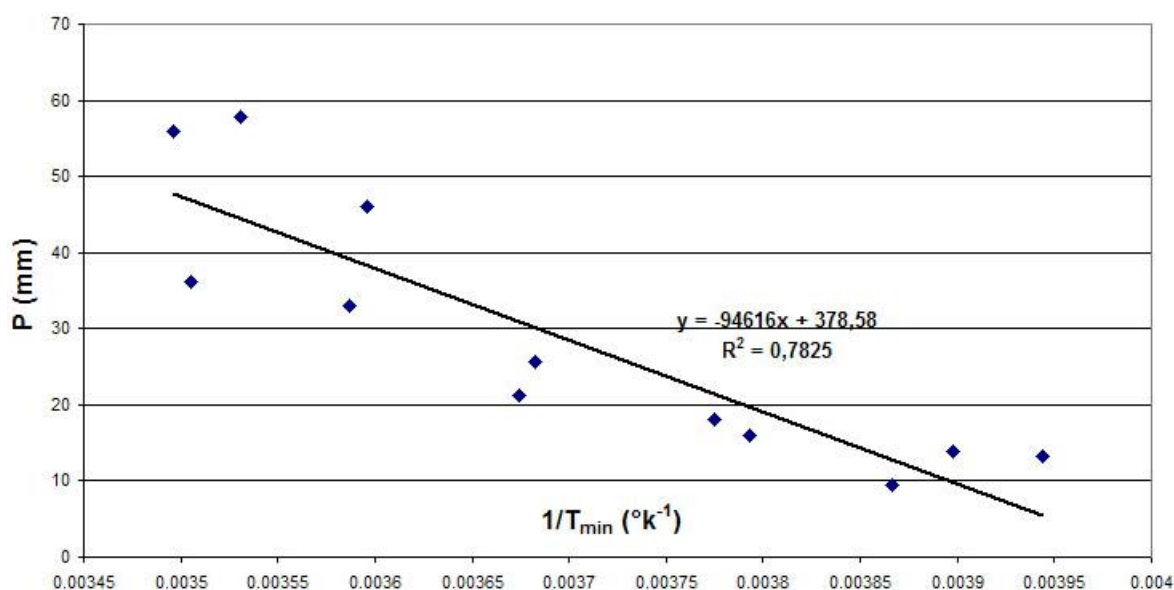

The chart shows a plot of P (mm) on the y-axis versus $1/T_{min}$ (°k^{-1}) on the x-axis, with the trend line equation $y = -94616x + 378,58$ and $R^2 = 0,7825$.

Figure 10—Climatologic chart of Willistone (North Dakota) January-December 1971 to 2000.

Hyper-Mediterranean Climate in San Diego (CA, USA)

The San Diego climate belongs to west-facing continents climate, a particular case of Mediterranean climate that we'll called "Hyper-Mediterranean." Among this type of climate we also find Mexico, Chile, South Africa (Le Cap), West Australia (Brisbane).

They are characterized by an attenuation of precipitation along the year compared to precipitation we observe in Mediterranean climate. The expression of this attenuation is of an exponential form and leads to a new expression of the climatologic charts:

$$(4) \quad \text{Log } P = A \, / \, T - B$$

A and B being characteristic constant of the meteorological station.

In order to study the interaction between wildfire and climate data of San Diego, we chose the year 2005 because its summer was abnormally warm. Monthly occurrence of fires in southern California was taken from N.I.C.C. 2005 data. As shown in figure 11, the equations are:

$$\text{Log } N_{2005} = -1.4202 \text{ Log P} + 3.34$$

$$\text{Log } N_{2005} = -28,674 \ / \ T + 99.04$$

The identification gives us:

$$(4') \quad \text{Log P} = 20,190 \ / \ T - 67.38$$

Compared to climatologic chart of San Diego 2005, the agreement is satisfactory:

$$\text{Log P} = 16,835 \ / \ T - 56.012 \qquad (R^2 = 0.46)$$

In order to study a possible climate change in San Diego, we established its climatologic chart for two annual periods 1927 to 1932 (a) and 1995 to 2004 (b):

$$(a) \quad \text{Log P} = 30,823 \ / \ T - 104.33 \qquad (R^2 = 0.87)$$

$$(b) \quad \text{Log P} = 12,028 \ / \ T - 40.23 \qquad (R^2 = 0.73)$$

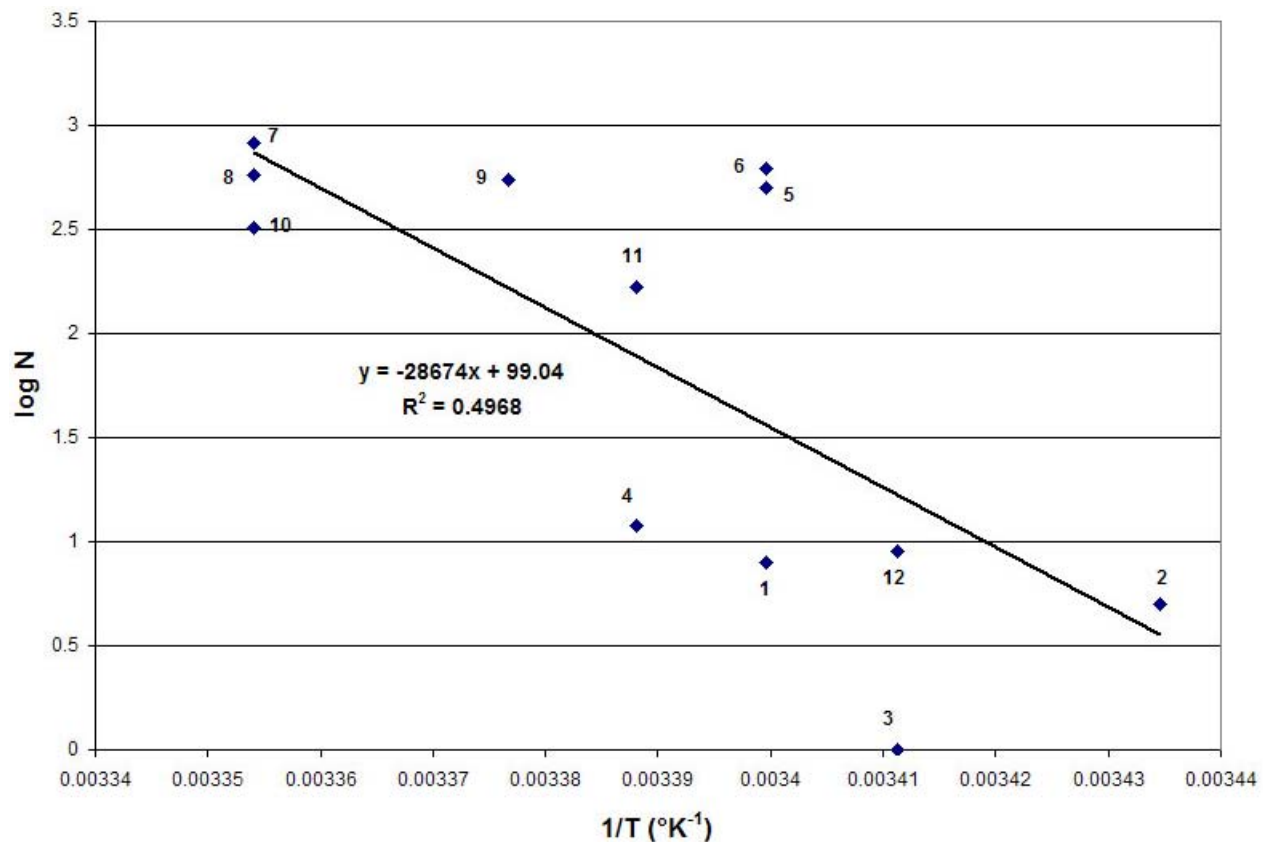**Figure 11**—San Diego, 2005. Log N = f(T).

In analogy with the equations found for the Mediterranean climate, we will use for the Hyper-Mediterranean one, the next method of reconstruction:

(1)   Log N = a + b * Log P

(2)   Log N = c − d / T

Identifying the two equations, we get:

(3)   Log P = (c−a) / b + d / (b *T)

Comparing the coefficient of the 1927 to 1932 period to the 1995 to 2004 period, we observe:

- The only variation of the "b" term. A 61 percent reduction of term "b" expresses the increasing value of aridity in the San Diego climate.
- A stability of the "d" term (containing the activation energy).

Wildfires and Global Warming

A particular interest for the effect of temperature on wildfire comes from global warming. Recent well documented publications of Westerling (2006) and Running (2006) analyze the different causes of increasing wildfire activities with global change, particularly in the Western United States of America.

In our own analyses of large wildfires in southern California in October 2003 (Bernard and Nimour 2004b), we pointed out an abnormal temperature rise in the region some days before the start of large landfires (Bernard and Nimour 2004d).

Conversely, the statistics of annual fires in Yellowstone National Park (1700 to 1990) show no fire during the little ice age (compare "Interpretation of fire intensity in Yellowstone National Park for the 1700-1990 period," Bernard 1998a).

Using the Arrhenius models of occurrence of fire and burnt areas:

$$\text{Log } N_2 - \text{Log } N_1 = - E^n_{act} / (2.3 \text{ R}) (1 / T_2 - 1 / T_1)$$
$$\text{Log } A_2 - \text{Log } A_1 = - E^n_{act} / (2.3 \text{ R}) (1 / T_2 - 1 / T_1)$$

A "theoretical" evaluation of the effect of global warming on natural forest fire was performed in 2004 (table 1). Different cases have been considered according to the two different fire classes (class 1 and class 3) and the two natures of control (UV lightning and PAR)

Table 1—Implication of global warming on natural forest fires.

Remarks	ΔT (°C) ($t_0 = 21$°C)	Control by UVB E_{act} = 392 KJ/mole		Control by PAR E_{act} = 271.5 KJ/mole	
		Coefficient for N or A [a]	Coefficient for A [b]	Coefficient for N or A [a]	Coefficient for A [b]
	0	1	1	1	1
	+0.5	1.3	2.23	1.20	1.44
Reference : 1900-2000 (Papadopol 2000)	+0.77	1.5	3.50	1.33	2.35
ESTIMATIONS	+2	2.9	25.3	2.10	9.26
21st century	+5	13.72		6.12	
Extreme thermal event	+10	192	(Re-evaluation of basic hypothesis)		
Little ice age (no sunspot)	−2	0.33	0.04	0.48	0.1

[a] Class 1 fires : Δ log A = Δ log N
[b] Class 3 fires : Δ log A = 3 Δ log N

Productivity and Climate Parameters

Net primary productivity, biomass, and associated environmental variables are now publicly available for 53 detailed study sites, of which more than half have data for belowground biomass or biomass dynamics. Aboveground NPP ranges from 35 to 2320 g.m^{-2}.year^{-1} (dry matter) and total NPP from 182 to 3538 g.m^{-2}.year^{-1}. These data are available from the Oak Ridge National Laboratory Distributed Active Archive Center (Scurlock and Olson 2002).

According to Lieth and Whittaker (1975), the range of NPP in g.m^{-2}.year^{-1} is: for tropical rain forest 1000 to 3000, warm temperature mixed forest 600 to 2500, Tundra 60 to 1300, Mediterranean sclerophyll forest (chaparral) 250 to 1500.

According to Gray (1982), when he studied productivity in southern California, the annual aboveground primary production in *Ceanothus Chaparral* was 1056 g.m^{-2}.year^{-1} and in Costal Sage scrubs 355 g.m^{-2}.year^{-1}.

We will refer for our studies to the original works made by Lieth and Whittaker (1975) on modeling of the primary productivity of the world.

Lieth and Whittaker Data

Lieth and Whittaker (1975) have summarized the net primary productivity of four large zones in the world, each of them containing from 12 to 20 ecoregions with their climatic data of precipitation in millimeters and temperatures in Celsius degrees.

For each zone, we analyzed the correlation between net primary productivity with precipitation and with Kelvin temperature according to the Arrhenius term (table 2). Identifying the two correlations, we obtain an expression of precipitation as function of 1 / T (table 3). For the three first regions, the agreement is satisfactory in spite of their low square regression coefficients.

We have particularly examined the fourth region results, which has the best square regression coefficient. In this zone, the net primary productivity is among the highest of the world, up to 4,000 gr per square meters by year (Lieth 1962).

Table 2—Net primary productivity (NPP) as functions of precipitation (P) and temperature (T).

Zone	**NPP = f(P)** **NPP in g/m^2.year ; P in mm**	**NPP = ϕ(T)** **T in Kelvin**
1	NPP = 0.528 P + 727.3 R^2 = 0.24	NPP = -2.10^6 (1/T) + 7 881 R^2 = 0.23
2	NPP = 0.4651 P + 858.8 R^2 = 0.11	NPP = -2.10^6 (1/T) + 8 403 R^2 = 0.11
3	NPP = 0.849 P + 356.7 R^2 = 0.19	NPP = -2.10^6 (1/T) + 6 603 R^2 = 0.20
4	NPP = 0.710 P + 911 R^2 = 0.46	NPP = -6.10^6 (1/T) + 22 074 R^2 = 0.65

Table 3—Climatologic charts from productivity and from climate data.

Zone	Chart from productivity f(P) = φ(T)	Chart from climate data
1[a]	P = −3.79 10^6 (1/ T) + 13 554	P = -3 10^6 (1/ T) + 12 832 R^2 = 0.79
2	P = −4.3 10^6 (1/ T) + 16 229	P = −4 10^6 (1/T) + 15 098 R^2 = 0.79
3	P = −2.35 10^6 (1/ T) + 7 348	P = −2.10^6 (1/T) + 6 603 R^2 = 0.20
4	P = −8.44 10^6 (1/ T) + 29 782	P = −5.10^6 (1/T) + 19 454 R^2 = 0.57

[a]Excepted October data.

So the net primary productivity of region 4 as function of temperature is:

$$P_2 - P_1 = 6* \; 10^6 \left(1 / T_2 - 1 / T_1\right)$$

P expressed in g/ m^2/year and T in Kelvin degrees.

In the same publication, Lieth and Whittaker (1975) proposed an empirical equation of productivity Y as a function of Celsius degrees X:

$$Y = 3,000 / \left(1 + e^{1.315 - 0.119X}\right)$$

Converting temperature data from Celsius to Kelvin degrees, we obtain an expression of productivity containing an Arrhenius term:

$$P_2 - P_1 = \text{Constant} \left(1 / T_2 - 1 / T_1\right)$$

Taking 10 values of temperature between −13 °C and +28 °C, we obtain an Arrhenius law of net primary productivity with a **square correlation coefficient very close to 1** (fig. 12)**.**

$$P = 5*10^6 / T + 19,320 \qquad\qquad (R^2 = 0.979)$$

Wildfire Net Primary Productivity and NDVI

The values of the normalized difference vegetation index (NDVI) extracted from satellite sensor data acquired by the National Oceanic and Atmospheric Administration's Advance Very High Resolution Radiometer (NOAA – AVHRR) have often been used for estimating forest fire risks.

According to Fang and others (2001), to examine the relationship between variability of NPP and precipitation at a broad scale, a long-term NDVI data set coupled with a historic climate data set constitute a useful and power-ful data source, because NDVI data are strongly correlated with terrestrial NPP.

The relative greenness (R.G.) was described by Burgan and Hartford (1993) as expressing how green each cell is relative to the range of greenness. Relative greenness, which has been used by Burgan and others (1998) for the evaluation of fire potential index (F.P.I.), indicates that it is a potentially valuable fire management tool for land management agencies.
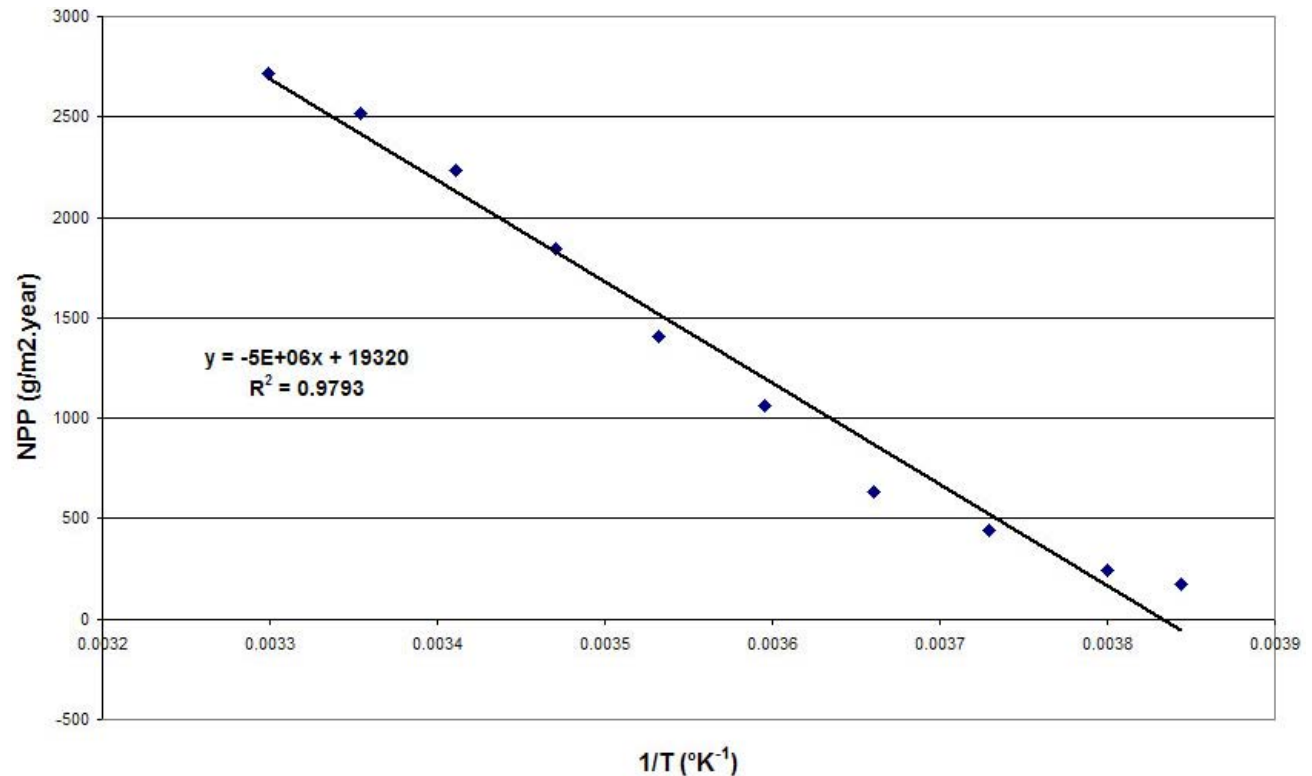
Figure 12—NPP = f(1/T). Data from Lieth and Whitaker (1975).

Gabban and others (2006) proposed a use of a new index referring to the dynamic relative greenness index (DRGI), to consider the interannual variability of NDVI at each precise location within the studied region. It was computed over the European Union countries and tested in Spain, France, and Italy. DRGI values and the number of fires were fitted using an exponential model. The testing of the DRGI over the 13 years showed a high correlation ($R^2 = 0.94$) between the number of fire outbreaks and the level of risk determined by the index.

So, this statement introduces the number of fires on a logarithmic form as a linear increasing function of DRGI.

Conclusions

It was established that the fire monthly frequencies are linearly correlated with precipitation. With regard to the temperature, the fires frequencies are narrowly correlated with the Arrhenius factor (1/T, T in Kelvin degrees) translating the existence of a regulating photochemical activation phenomenon (PAR or UVB according to the season). All these correlations can be found on a multiannual scale.

The reconstruction of the studied area climate can be carried out by identifying the expressions of the frequency of fires in function of precipitation and temperature. We proposed the concept of "climatologic chart" (Bernard and Nimour 2004) starting from such reconstruction process. This graphical

representation method of the "climatologic chart" that we introduced starting from the climate data, P= F (1/T) is fully justified by the highlighted vegetation production laws.

Indeed, the net primary productivity is expressed in function of precipitation or temperature, through laws similar to those found on the fires frequency in log scale on an interannual scale. That brings an answer to the questions that we had on the role of the biomass production in the fires frequency laws. Moreover, the NDVI and its interannual variability, which are closely linked to the vegetation production and the fires statistics, still reinforce this similarity.

The proposed model set will constitute valuable tools for the study of the climatic changes and their repercussions on the fires regimes, aridity, and stability of vegetation communities and may contribute to developing new fire management strategies as expressed in the San Diego declaration on climate changes and fire management.

References

Bernard, M.L. 1998a. Interpretation of fire intensity in Yellowstone National Park (1700-1990). Lecture at Y.N.P., May 29 1998; USA.

Bernard, M.L. 1998b. Wildland fires, sunspot and solar flux: a tentative of correlation. 3rd International Conference on Forest Fire Research, 14th Conference of fire and Methodology, 16-20 November 1998; Coimbra, Portugal.

Bernard, M.L.; Carbonel, M.; Nimour, N. 2000. Are large wildland fires –as anomalous ecological processes- natural hazards. Phys. Chem. Earth (A). 25 (12): 763-768.

Bernard, M.L.; Lleras, J.; Nimour, N. 1999. Wildland fires, solar flux and total ozone content of the atmosphere: mutual correlations. European Geophysical Society 24th General Assembly; The Hague, Netherlands.

Bernard, M.L.; Nimour N. 2004a. A concept of climatologic chart. EMS Annual Meeting Abstracts. 1 (00286). European Meteorological Society.

Bernard, M.L.; Nimour N. 2004b. Large fires in South California, October 2003: climatologic analysis, theory and reality. Geophysical Research Abstracts. 6 (00339). European Geosciences Union.

Bernard, M.L.; Nimour, N. 2004c. Lightning fires dependence on precipitation and temperature. Geophysical Research Abstracts. 6 (00354). European Geosciences Union.

Bernard, M.L.; Nimour, N. 2004d. Short-range forecasting of large wildland fires. EMS Annual Meeting Abstracts; 1 (00285). European Meteorological Society.

Bernard, M.L.; Nimour, N. 2005a. Application of the concept of climatologic chart to Mediterranean climate variability. Geophysical Research Abstracts. 7 (01839). European Geosciences Union.

Bernard, M.L.; Nimour N. 2005b. Reality of the climatologic theory of wildland fires based on UV-B efficiency. **Geophysical Research Abstract. 7 (2906). European** Geosciences Union.

Boullard, B. 1993. De la poudre aux incendies de forêts…une approche canadienne. La Forêt Privée. 212: 84-87.

Burgan, Robert E.; Hartford, Roberta. 1993. Monitoring vegetation greenness with satellite data. Gen. Tech. Rep. INT-297. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Despain, D.G. 1998. Personnal communication.

Douglas, Arthur V.; Stockton, Charles W. 1975. Long-term reconstruction of seasonal temperature and precipitation in the Yellowstone National Park region using dendroclimatic techniques. The University of Arizona. Prepared for United States Department of the Interior, National Park Service, Yellowstone, WY.

Douguedroit, A. 1992. Sécheresse et incendies de forêts en region mediterranéenne. Revue d'Analyse Spatiale Quantitative et Appliquée. 22. Colloque International «Le feu; avant-après». Nice, France.

Fang, J.; and others. 2001. Interannual variability in net primary production and precipitation. Science. 7 September 2001. 293 (5536): 1723.

Flannigan, M.D.; Wotton, B.M. 1991. Lightning ignited forest fires in Northwestern Ontario. Canadian Journal of Forestry research. 21: 227-287.

Forgeard, F. 1994. Importance and characteristics of heathland fires in Brittany (France). 2nd Int. Conf. Forest Fire Research. 1 (B 28): 447-458.

Frontier, S.; Pichod, Viale. 1991. Ecosystèmes, structure, evolution. Collection d'écologie. Masson.

Gabban, A.; San-Miguel-Ayanz, J.; Barbosa, P.; Liberta, G. 2006. Analysis of NOAA-AVHRR interannual variability for forest fire risk estimation. International Journal of Remote Sensing. 27 (8), 20 April 2006: 1725-1732.

Gray, J.T. 1982. Community structure and productivity in Ceanotus Chaparral and Coast Sage Scrubs of South California. Ecologic Monographs. 52 (4), December 1985: 415-435.

Humbert, J.; Najjar, G. 1992. Influence de la forêt sur le cycle de l'eau en domaine tempéré. Une analyse de la littérature francophone. CEREG, Université de Strasbourg I, France.

Latham, D.J.; Rothermel, R. 1993. Probability of fire stopping precipitation events. Res. Note INT 410. Ogden, UT: United States Department of Agriculture, Forest Service, Intermountain Research Station.

Lieth, Helmuth; Whittaker, M., eds. 1975. Productivity of the biosphere. Springer-Verlag.

NICC. 2005. Incident Management Report 2005. South California National Interagency Fire Center.

Nimour, N. 1997. Flammability of the Mediterranean vegetation. Thesis. Laboratoire de Chimie et Environnement, Université de Provence. Marseilles, France.

Olivier, L. 1975. Première contribution à l'étude de l'intervention de la végétation et de certains facteurs écologiques dans les incendies de forêts en Basse Provence. Doctorat de spécialité. 28 february 1975. Université d'Aix-Marseille III (Saint-Jérôme). Marseilles, France.

PROMETHEE. 1985-1997. Forest fires database. Conseil General des Bouches-du-Rhône, France.

Ramade, F. 1994. Eléments d'écologie. Ecologie fondamentale. Ediscience International.

Rambal, S. 1984. Water balance and pattern of root water uptake by Quercus coccifera L. evergreen scrub. Oecologia (Berlin). 62: 18-25.

Romme, W.H.; Despain, D.G. 1989. The long history of fires in the Greater Yellowstone ecosystem. Western Wildlands. 15: 10-17.

Running, Steven W. 2006. Climate change: is global warming causing more, larger wildfires? Science. 313 (5789). 927.

Scurlock, J.M.; Olson, R.J. 2002. Terrestrial net primary productivity—A brief history and a new worldwide database. Environ. Rev. 10 (2): 91-109.

Terol, C.M.M. 1987. Incendios forestales en Alicante; Publicaciones de la Caja de Ahorros Provincial. 143. Alicante, Spain.

Trabaud, L. 1980. Impact biologique et écologique des feux de la végétation des zones de garrigues du bas-Languedoc. Thesis. Université des Sciences et Techniques du Languedoc. France.

Viegas, D.X.; Viegas, M.T. 1994. A relationship between rainfall and burned area in Portugal. International Journal of Wildland Fires. 4 (1): 11-16.

Ward, P.; Wotton, M. 1994. Personnal communication.

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase Western US forest wildfire activity. Research articles. Science. 313 (5789): 940-943.