REAL TIME MONITORING OF VEGETATION FLAMMABILITY USING NOAA-AVHRR THERMAL INFRARED DATA

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ABSTRACT

In order to improve daily fire danger prediction in French Mediterranean Forests, the Cemagref-ENGREF remote sensing laboratory has developed a vegetation water stress index based on the use of NOAA-AVHRR thermal infrared and meteorological data. The « *Stress Index* » is equal to $SI=1-LE/LEp$, where *LE* is the actual evapotranspiration and *LEp* the potential evapotranspiration. A first study, on 11 French forested areas, from July to September 1994, showed that the stress index was positively correlated with the probability of large fires. Moreover, real-time stress index maps could enable forest managers to locate drier areas. In a second step, stress index values were related to measurements of flammability parameters (relative water content, ignition delay) in several sites in *Les Maures* forest (southern France). Increases in *SI* corresponded with decreases in ignition delay and thus with an augmentation of vegetation fire susceptibility. Therefore, *SI's* temporal variations could be used as an indicator of vegetation flammability to complement existing meteorological fire danger indices. Moreover, satellite images provide a spatial information concerning the variability of the vegetation susceptibility to fire.

1. INTRODUCTION

French Mediterranean Forests are regularly subject to a large number of fires. Because of an intense summer drought, 10,000 to 60,000 hectares are burnt every year. Most of the current fire danger indices are based on meteorological data such as air temperature, air humidity and wind speed (Drouet, 1982; Carrega, 1991; Sol, 1989; Van Wagner, 1987). But daily estimation of vegetation flammability for large areas remains difficult. Direct measurements of fuel moisture require costly spatial sampling and cannot therefore be generalised to all forested areas. If it is proven that satellite images can provide information on vegetation water status, which is a crucial parameter of the fire danger, then it could give exhaustive spatial data over large areas.

For agricultural canopies, the use of NOAA-AVHRR thermal infra-red has been successful for estimating the daily evapotranspiration which is closely related to the water stress (Seguin & al., 1989; Vidal & Perrier, 1990; Kerdiles & al., 1990). And according to Seguin, 1990, this method could be applied to vegetation moisture estimation in forested areas.

Since 1991, the Cemagref-ENGREF Remote Sensing Laboratory has been developing a method for monitoring vegetation water stress. A vegetation water stress index, subsequently called *"Stress Index"* or *SI*, has been developed, based on daily NOAA-AVHRR thermal infrared and local meteorological data (Vidal et al., 1994). It is derived from the ratio between actual evapotranspiration, *LE*, and potential evapotranspiration, *LEp*. In a first step, this method was tested in 1994 on some large forested areas of the French Mediterranean region. The objective was to test the possibility of estimating vegetation water status in operational conditions and to identify areas with high flammability. In a second step, the Stress Index has been correlated with flammability parameter measurements made in *les Maures* forest by the French *Institut National de la Recherche Agronomique* (INRA).

2. THEORY

Due to its high repetitivity (two images per day, of which one in the early afternoon, when fire danger is the highest), NOAA-AVHRR is well adapted to daily vegetation monitoring.

Its large observation field covers in one passage the whole French Mediterranean region and its two thermal infrared bands (4 and 5) allow atmospheric and emissivity corrections (Vidal, 1991). Its low spatial resolution (1.1 km at nadir) is adapted to regional scale but limits its use to homogeneous areas of vegetation.

Canopy evapotranspiration appears to be a good indicator of plant water status because it directly depends on the ability of the plant to exchange energy with the environment through latent heat flux (Vidal et al., 1994). Canopy instantaneous evapotranspiration can be related to its instantaneous remotely sensed surface temperature through the surface energy balance equation, with the following expression:

$$Rn = G+H+LE\,,$$

where Rn is net radiation, G soil heat flux, H sensible heat flux and LE latent heat flux or actual evapotranspiration. Consequently:

$$LE = (Rn - G) - \frac{\rho Cp}{(r_a + r_o)}(Ts - Ta)\,,$$

where Ts and Ta are respectively the surface and air temperatures, rCp the volumetric heat capacity of air, r_a the aerodynamic resistance and r_o the structural resistance due to stratification of the leaves in the canopy (Perrier, 1975).

When a plant lacks water, it reduces its water loss by closing its stomata; consequently LE is reduced and, as net radiation is constant, H increases. Thus, surface minus air temperature (Ts-Ta) becomes higher. LE can be estimated from satellite derived surface temperature and synoptic meteorological data. The potential evapotranspiration, LEp, which is reached when all the exchanging surfaces are saturated, is estimated only from synoptic meteorological data, with a classical expression given by many authors (see for example Jackson et al., 1981).

The ratio LE/LEp ranges from 0 to 1. It as be shown that a decrease in its value corresponds to an increase in the number of fire events (Vidal et al., 1994). To have a positive relationship between the index and the fire danger, the "Stress Index", SI, is equal to (1-LE/LEp). When it increases, the water stress increases, and if other risk factors are present (human pressure, high winds...), the number of fires is high. If not, it remains low.

3. METHODOLOGY

Validation of fire danger indices is difficult because fire danger depends on many factors, and especially, anthropic pressure. Two assessment methods were chosen. They consist of relating the Stress Index with 1) fire events and 2) flammability parameters such as moisture content and ignition delay.

The study was organized in three steps:

1. Evaluation of the interest of the Stress Index in operational conditions, by an a posteriori study concerning the 1991 (dry) and 1992 (wet) summers, in one study area, Les Maures forest.

This large forest (888 km²) is located in Southern France between Toulon and Saint-Raphaël (*Figure 1*). Well individualised and rather homogeneous, this area is mainly covered by cork oak (*Quercus suber*), in association with holm oak (*Quercus ilex*) and pines (*Pinus halepensis, Pinus pinaster)* and various types of shrubs, especially heather (Erica arborea). This vegetation grows on acid soils. Elevation ranges from 0 to 780 m and the topography is rough. Fire danger is closely associated with a N-NW wind, the Mistral, violent, sudden and dry.

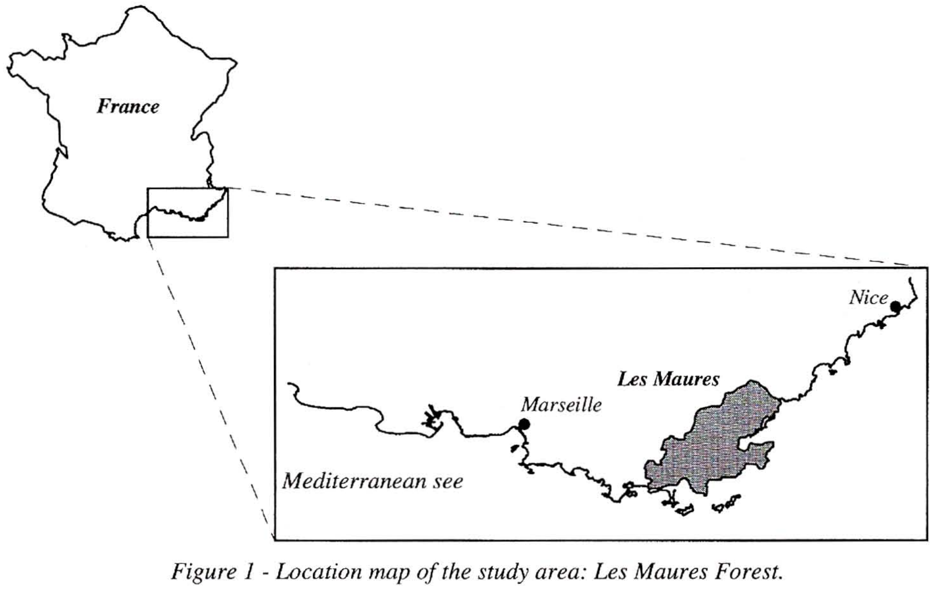

Figure 1 - Location map of the study area: Les Maures Forest.

A series of NOAA-AVHRR-11 images (only thermal infrared bands, 4 and 5) covering France on a daily basis from mid-June to late September were used to compute the Stress Index. All daily images acquired during the afternoon pass were provided by the *Centre de Météorologie Spatiale* (Lannion) (Météo-France). This series consist of an archive of images, geometrically corrected with a 500-m precision and then compressed to a 2-km resolution by averaging each 4-pixel square. A cloud mask was also provided, allowing information limited to clear pixels (Derrien et al., 1992). Black body surface temperatures were computed from the AVHRR thermal bands 4 and 5 (respectively T_4 at 10.33-11.3 µm and T_5 at 11.5-12.5 µm) and corrected of the atmospheric and emissivity effects, using land surface temperature split-window equations (Vidal, 1991; Melia et al., 1991). Images with view angles higher than 35° were not used to avoid great imprecision due to the severe degradation of the spatial resolution.

Meteorological data, necessary for the computation of the stress index, were obtained from Le Ruscas station. This station, located in the center of the forested area, is considered as representative of this area. The data (air temperature and humidity, wind speed, global radiation) were measured at a height of 2 m above a grass canopy, at the time of the satellite overpass. Theoretically, the air temperature, which is the most important factor of the Stress Index equation, should be measured above the forest canopy. However, computation of LE/LEp have been done in a study area near Montpellier (*Puéchabon* forest) using air temperature at 2 m and above the forest canopy. The results with the two temperatures were similar *(Durand, 1991)* Therefore, we will use the standard data given by the meteorological stations.

Fire events were ascertained from the French PROMETHEE database, which locates daily fires on a 2x2 km raster grid along with the spatial extension, cause and other ancillary information. The information query from this database can be made through a telematic server (Minitel). Only fires that yielded a burnt surface of more than 1 ha were used. According to French fire-fighting experts, this threshold better represent the natural hazard to be estimated. Under 1 ha, it is difficult to know if the fire did not spread because of the natural conditions (vegetation, wind) or because of the good efficiency of fire-fighting means. Above 1 ha, considering the usual efficiency of the surveillance means, the fire may have extended quickly because of critical natural conditions (vegetation drought, wind) before the fire-fighting units could attack it.

For the whole study area, on each day with a cloudless image, an average Stress Index was computed from the average surface temperature on the area and the meteorological data provided by the Ruscas station. *SI*, calculated from D day data, was considered as a prediction for the (D+1) day. Thus, it was related with fire events occurring on (D+1) day, as well as with predicted meteorological fire danger indices. The Stress Index, which provides only information about vegetation status, cannot be used alone. Therefore, a decision rule, was established on July and September data and later applied to June and August data, allowed combining *SI* with a meteorological index of fire danger called, Numerical Risk, (Sol, 1989; Drouet et Sol, 1990). In operational terms, the Numerical Risk values correspond to three fire danger levels: low, high and very high. Thus, to make the stress index comparable, its values where distributed in 3 levels : low when $IS < 0.75$, high when $IS \in [0.75, 0.85]$ and very high when $IS > 0.85$.

2. Real-time use of the Stress Index during Summer 1994, in an operational situation for eleven large forested areas of the French Mediterranean region.

The NOAA-AVHRR-11 images were pre-processed by the *Centre de Météorologie Spatiale* as it had been described above. They were daily transmitted to the Cemagref-ENGREF remote sensing laboratory through Internet during the following night. The meteorological data, measured at the time of the satellite overpass, in meteorological stations distributed inside each study area, were faxed during the morning by Météo-France. An average stress index was computed for each forested area (from 450 to 900 ha) with the average surface temperature and the average meteorological parameters (when there were several stations inside one study area). Daily estimations of the average index computed for each forested area, as well as surface temperature images used as local representations of water stress spatial variability were transmitted by fax to the CIRCOSC (interregional centre for coordination of civil security operations). In order to show if the Stress Index could improve daily predictions, it was compared with other danger indices and fire events. It was also correlated with meteorological conditions (rain, wind).

3. Correlation with flammability parameter measurements during the summer 1994, in Les Maures.

Since 1989, the French *Institut National de Recherche Agronomique* (INRA) has done flammability measurements on *Erica arborea*, in *Les Maures* forest.

The flammability parameters and the measurement method have been described in several publications (see for example Valette & Moro, 1994). Two flammability parameters were related to the Stress Index: the Ignition Delay, *ID*, (the mathematical average of the ignition delay of 50 tests) and the Dryness Index, *DI*. The ignition delay, measured with an epiradiator, corresponds to the delay between the instant when a sample of terminal shoots of vegetation is put on a heat source and the instant when the volatile gases ignite. It decreases with moisture content.

The Dryness Index increases when the moisture content decreases. It is calculated with the following equation (Valette et al., 1994):

$$DI = 200 \times DW/FW - 100$$

where *DW* is the dry weight (samples are left at least 24 hours in an oven at 60°C) and *FW* is the fresh weight of terminal shoots of plants.
In 1994, measurements of flammability parameters were performed on *le Ruscas* site, during the hottest hours of the day, three times a week, from mid-June to mid-September. The dryness index, was measured twice a week on *Erica arborea* at 17 sites scattered in Les Maures forest. *Erica arborea* is largely present in the French Mediterranean « maquis ». These shrubs constitute a continuous understory in *Quercus suber / Pinus pinaster* stands and can be find in open stands.

In order to compare flammability parameters and the Stress Index, it was first necessary to select the most homogeneous sites. Because of the satellite resolution (1 km), we had to find sites within homogeneous area of shrub lands of about 2x2 km (2x2 pixels : to reduce the errors of geometrical corrections) so that the fuel moisture measurement was representative for the entire site. Only 4 sites were selected: the Ruscas site, where the ignition delay and the dryness index were measured and three others, with only the dryness index measurements. The Stress Index was computed with the weighted average of surface temperature (in an area of 2x2 km centred on the measurement site) and with meteorological data recorded at the Ruscas station.

4. RESULTS

4.1. First stage : Summers 1991& 1992

Combination of the Stress Index and the numerical index of fire danger (NUMERICAL RISK) reduces false alarms (high or very high danger predicted whereas no fire occurred) by 23% and missed alarms (low danger predicted whereas at least one fire, greater than 1 hectare occurred, or moderate danger predicted whereas at least one fire, greater than 10 hectare occurred) by 25% compared with the numerical index of fire danger alone (Desbois & Vidal, 1995).

4.2. Second stage: Summer 1994, relation with meteorological data and fire events

- Comparison with meteorological data:
  Rainy periods were always followed by a decrease in Stress Index values, whereas windy spells corresponded to an increase in values. Indeed, turbulence created by wind at leaf surface induce stomata to close and thus decrease evapotranspiration.
- Comparison with fire events:
  Higher Stress Index values were associated with a larger average of burned surface per fire. Thus, for SI $\geq$ 0.95, this surface reached 57 hectares, whereas for SI $<$ 0.85 it fell to 0.36 hectares. Likewise, higher Stress Index values were associated with greater number of fire events: on average 0.30 per day of observation for SI $\geq$ 0.95 and only 0.09 for SI $<$ 0.85. Only the fires larger than 1 ha are considered for the reasons defined before. Figure 2 shows that all large fire (> 50 ha) had occurred when the Stress Index was higher than 0.85. Moreover, the ignitions are more frequent for the values of the Stress Index higher than 0.85. However, many little fires (>10 ha) are observed for high values of the Stress Index: even if the vegetation is dry, if the fire fighting means arrive very quickly (quick detection, easy access, no simultaneous fires...) the fire will be stopped before it could extend. On the contrary, 2 fires of more than 10 ha occurred when the Stress Index was lower than 0.85. This points out the difficulty to assess fire danger indices with fire events. Too many factors influenced fire ignition and extension.

However, in several cases, meteorological indices predicted low danger essentially because of the lack of wind, whereas the Stress Index indicated a high or increasing vegetation water stress. Under such conditions, several fires occurred, especially large ones. This occurred in southern Corsica, where several large fires (4500 and 3800 hectares being the largest) broke out whereas meteorological fire danger indices did not forecast an increasing danger.
More than the absolute value, the Stress Index increase is a good warning, especially when other indices are low. Therefore, it is also a means to confirm the fire danger level predicted by other indices.

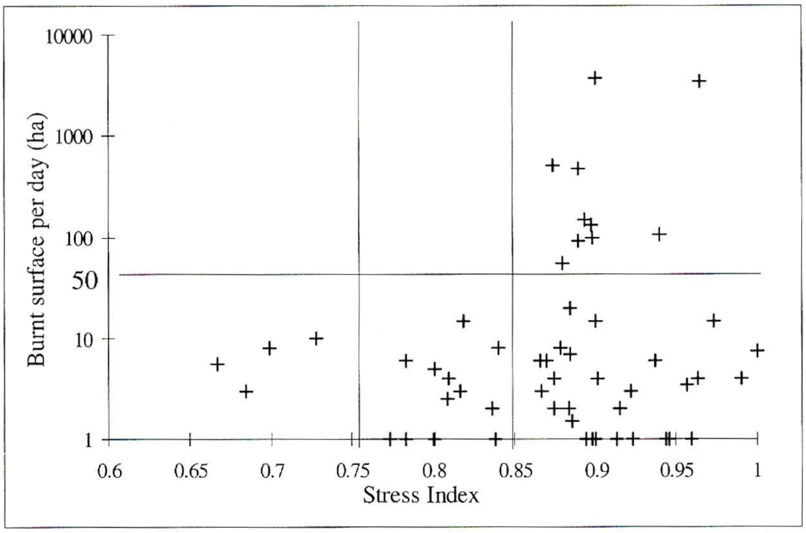

Figure 2 - Relation between stress index and daily burnt surface.

Furthermore, the surface temperature image defines the spatial variability of water stress. Thus, the location of fires on satellite images of the previous day showed that most of the fires and all the large fires (>50 ha) occurred in the warmest areas, which are also approximately the driest and therefore the most flammable (Desbois & Vidal, 1995).

Fire events (surface and number) are influenced by many other parameters than the vegetation drought, such as wind, topography, human pressure, fire fighting conditions... Consequently, fire surface is only a very indirect indicator of vegetation drought. This type of assessment is therefore insufficient and must be complemented by correlation with direct measurement of vegetation flammability.

4.3. Third Stage : Summer 1994, correlation with vegetation flammability parameters.

The temporal variation of stress index (*SI*) and dryness indice (*DI*) were compared. But it appeared that both indices measured different phenomena, since *SI* is an instantaneous value, whereas *DI* is a cumulative one which increases during the season. Consequently, we compared *SI* with: ① the derivative function of *DI*, *(DI)'*, which represents the variation between two consecutive measures (in order to make *DI* instantaneous) *(Figure 3)*, and ② the Ignition Delay *(Figure 4)*

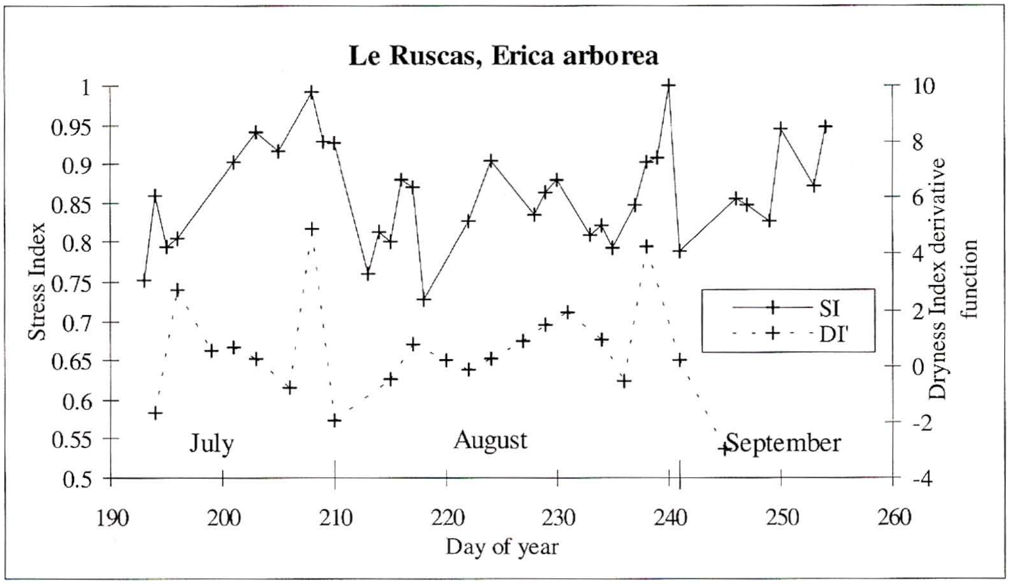

Figure 3 - Comparison of the temporal variations of the Stress Index (SI) and the dryness index derivative function (DI') at le Ruscas site (Erica arborea); Summer 1994.

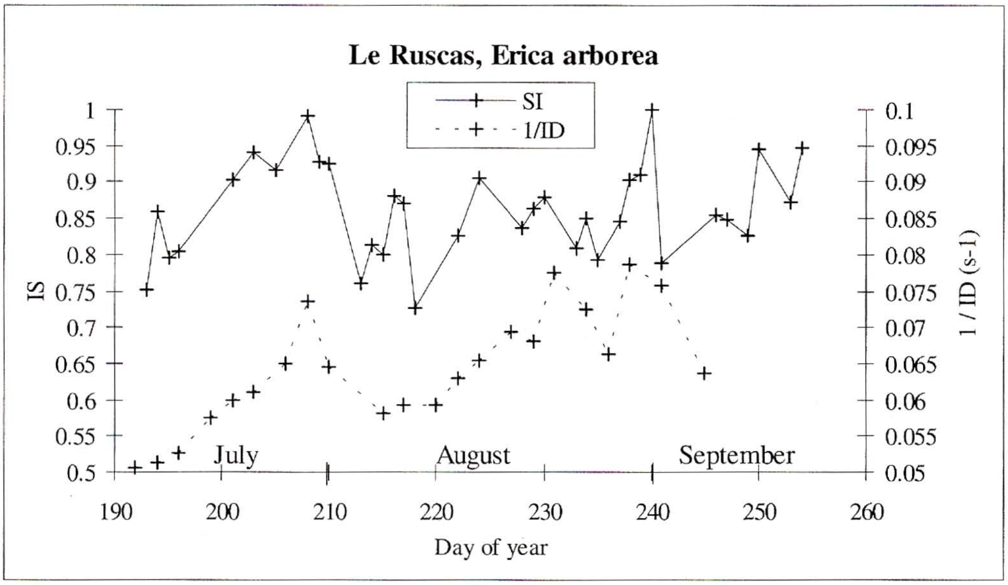

Figure 4 - Comparison of the temporal variations of the Stress Index (SI) and the Ignition Delay (ID) of Erica arborea at le Ruscas site; Summer 1994.

The Stress Index evolves throughout the study time period in a similar way as *(DI)'* and *1/ID*. The two main peaks, around days 208 and 241, are also visible on the Stress Index graph. The increase in *SI*, but not the flammability parameters, around day 215 corresponds to a windy period. The evapotranspiration is reduced, but the vegetation is not necessarily dryer. However, the fire danger is increased.

A linear equation was fitted on those days where both parameters were simultaneously known *(Figure 5)*.

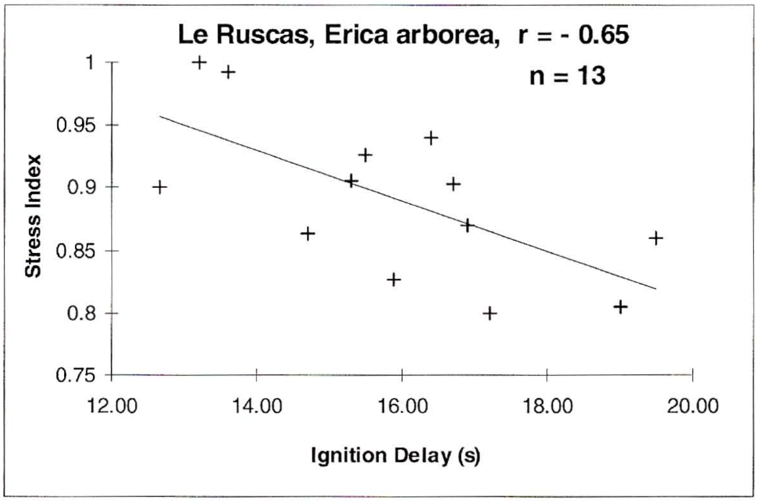

Figure 5 - Correlation between Stress Index and the Ignition Delay measured on Erica arborea, on the Ruscas site. Summer 1994.

There is a significant relation between the Stress Index and the Ignition Delay, (correlation coefficient, r = - 0.65). An increase in the Stress Index corresponds to a decrease in the Ignition Delay, which is highly correlated with relative water content (r = - 0.90 to - 0.96, Valette et al., 1994). The limited number of simultaneous measurements of Stress Index and this flammability parameter can partially explain the observed scatter in *Figure 5*. But especially, we compare punctual measurements on shrubs with values integrating vegetation status over 2x2 km. Moreover, the study period, from mid July to mid-September, is too limited and does not permit to cover the whole variation of the stress index (no value under 0.75). For these reasons, this study will be complemented by a campaign of fuel moisture content measurements during the summer 1995 (from mid-June to end of September), on more sites and more vegetal species.

6. CONCLUSION: OPERATIONAL USE PROSPECTS

Good relationships exist between the Stress Index and both burnt surfaces and flammability parameters (especially the Ignition Delay). On a period of 66 days of observation, on eleven forested areas, all large fires (>50 ha) were associated with high stress index values (IS>0.85). Increases in the Stress Index are linked with decrease in ignition delay and thus in water content. Therefore, the Stress Index should be a useful complement to other meteorological indices to characterize the vegetation flammability and especially to have an exhaustive spatial information about it. In order to compute a stress index for areas with a homogeneous vegetation type, a vegetation map should be used.

Whereas a daily Stress Index appears to be a good fire danger indicator, end-users of such monitoring methods are more interested in maps of vegetation water stress derived from NOAA-AVHRR data. But, such maps require the combination of 1-km resolution NOAA-AVHRR data and spatially distributed meteorological data, in order to compute *SI* for each pixel. A complementary study is currently made to develop models to produce 1-km resolution maps of meteorological data (especially the air temperature). Therefore, currently the main problem to produce Stress Index maps is the sparse geographical distribution of weather stations. The formulation of the stress index could be simplified to reduce the use of meteorological data. Thus, we could use only the difference between air and surface temperature (Ts-Ta). Indeed, Seguin et al., 1991, have shown close relationships between accumulated values of (Ts-Ta) and $\sum$LE - Rn (net radiation) over long term period and at regional scales. This relationship might be successfully applied to fuel moisture estimation (Chuvieco & Pilar, 1994). Other authors develop fire danger indices using only satellite data, such as NDVI by computing Greenness Indexes (Burgan and al., 1993) or NDVI and Surface Temperature (Prosper-Laget et al., 1994).

Further analysis will test statistical correlation between the Stress Index, a simplified stress index (for example $\sum$(Ts-Ta)) and fuel moisture content, on two supplementary areas (shrub lands near Aix-en-Provence and Montpellier) and on different species (*Rosmarinus officinalis, Quercus coccifera, Juniperus oxycedrus, Arbustus unedo*).

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