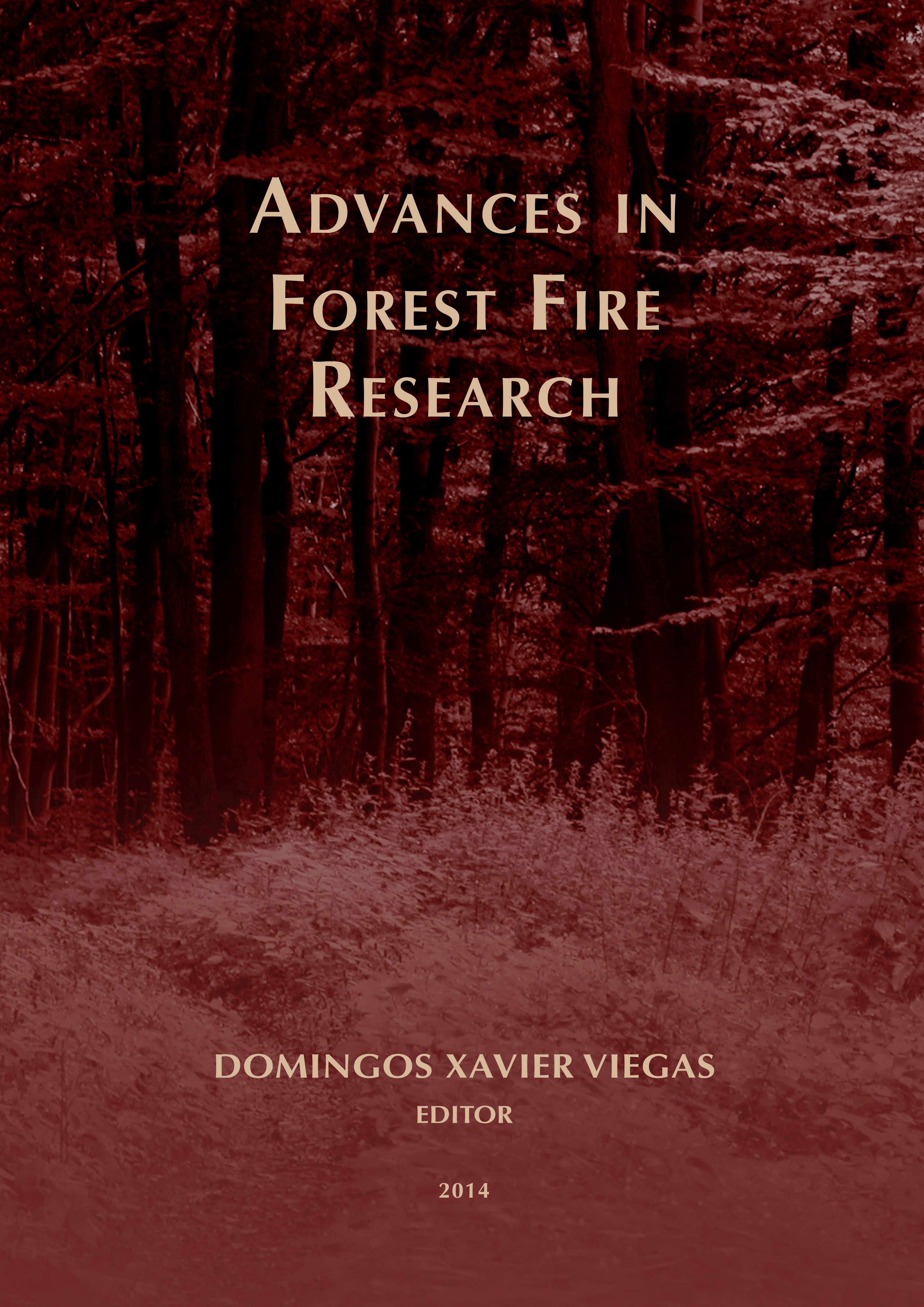

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Trends and changes of fire danger in Italy and its relationships with fire activity (1985-2008)

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Abstract
The comprehensive understanding of trends in fire activity and associated drivers is crucial to anticipate future trends and regulate fire potential impacts, by means of efficient fire and fuel management strategies. A valuable tool to examine past changes on fire potential and danger across fire regions is represented by fire weather indexes. In this study, spanning from 1985 to 2008, recent trends and patterns of fire danger and the relationships between the Canadian Fire Weather Index (FWI) System components and fire activity were investigated across Italy. Although time series trend analysis revealed a statistically significant increase in temperature, no clear pattern of fire danger increase was unveiled, while the number of days with high fire danger level increased significantly, especially in central and southern Italy. Monthly fire activity was modeled using as explanatory variables FWI components and significant coefficient of determination were obtained. The applied statistical approach (multiple linear regression) explained a consistent part of the fire occurrence variance all year long ($p<0.001$), although relevant differences across Italy were found.

***Keywords**: fire danger indexes, percentile analysis, trend analysis*

1. Introduction

According to the last Intergovernmental Panel on Climate Change (IPCC, 2014), observed climate trends showed a variation in temperature and rainfall over Europe. There are different degrees of confidence that future climate will show an increase in high temperature extremes (*high confidence*) and meteorological drought (*medium confidence*), but small or no changes in wind speed extremes (*low confidence*), with diverse patterns varying considerably within and between regions.
It is well known that extreme weather events, such as extended drought and heat waves, facilitate and promote forest fire activity in Southern Europe. For example, during the dry spells in 2005, 2007 and 2009 a high number of large wildfires were recorded in South European countries (Pereira *et al*., 2005; EEA, 2010c; Koutsias *et al*., 2013; Salis *et al*., 2013). Future fire risk is projected to increase in Southern Europe (Carvalho *et al*., 2011; Dury *et al*., 2011; Vilén and Fernandes, 2011; Lung *et al*., 2013), along with the occurrence of high fire danger days (Arca *et al*., 2012) and fire season length (Pellizzaro *et al*., 2010). In this framework, the analysis of past conditions and the factors that shaped fire pattern plays a crucial role for the comprehensive understanding of trends in fire activity, so as to anticipate future fire potential and changes (e.g., Carvalho *et al*., 2010; Zumbrunnen *et al*., 2011; Amatulli *et al*., 2013), and to assess the ecological effects of forest fires, thus reaping the benefits (Moreno and Chuvieco, 2012).
During the last decades, fire weather indexes were often used to examine past changes on fire potential and danger across fire regions (e.g. Camia *et al*., 2008; Carvalho *et al*., 2008; Mäkelä *et al*., 2012; Wastl *et al*., 2012). These systems, combining relevant weather variables into suitable indexes, are usually valuable tools to estimate potentially dangerous conditions, as fire intensity or large size fires, and to help forest fires services in effective prevention and response to forecasted danger. A clear comprehension of the relationships between these indexes and fire occurrence features, as well as their

efficiency, is of paramount importance in the implementation of fire policies and management (Carvalho *et al*., 2008; Bedia *et al*., 2012). Furthermore, the identification of areas with high fire danger and risk under severe and extreme environmental conditions is of utmost importance to cope and regulate their potential impacts through fire and fuel management (e.g. Fernandes, 2009; Arca *et al*., 2009; Salis *et al*., 2012b). Moreover, fire danger measurements are very valuable for all fire-fighting services, as they enable minimizing the level of uncertainty by combining scientific knowledge and operational experience (Valese 2008; Taylor and Alexander 2006).

One of the most commonly used fire danger rating systems across the world is the Canadian Fire Weather Index System (FWI), developed by Van Wagner and Pickett (1987). FWI has been very effective not only in Canada, where it was developed, but also in the Mediterranean area, as demonstrated in literature (e.g., Viegas *et al*., 1999; 2001). An important comparative study assessing the performance of different danger indexes in Southern Europe has revealed that FWI is the fire danger index best correlated with fire occurrence in Spain, France, Italy and Southern Portugal (Viegas *et al*., 1999). Therefore, FWI is a reliable fire danger system also in dry Mediterranean vegetation and climate conditions, which are very different from Canadian conditions where FWI was designed. However, despite its successful application in recent studies in Mediterranean regions (Moriondo *et al*. 2006; Valese 2008; Carvalho *et al*. 2008), it is noticeable that the performance of FWI and its relationship with fire occurrence show different response patterns according to the area considered (Carvalho 2008).

In relation to this, few works are available in Italy. With the intention to fill this knowledge gap and thus contribute to the understanding of past fire danger conditions, the main goals of this study are to (i) investigate and characterize recent trends and patterns of weather and fire danger in Italy, and then to (ii) unravel the relationships among the Canadian Fire Weather Index (FWI) System components and both fire number and burned area.

2. Methods

2.1. Study area and data collection

The area under investigation is Italy, which covers an area of about 301,000 km^2 comprising the boot-shaped Italian Peninsula and a number of islands including the two largest of the Mediterranean sea, Sicily and Sardinia. The climate of Italy, according to Köppen-Geiger (1954) climate classification, can be distinguished into 7 broad climatic regions, from the Mediterranean climate (characteristic of all coastal areas excluding the North-East) with mild and wet winter and hot and dry summers, to the Tundra climate with mean temperature below 10°C all year long. According to the Corine Land Cover classification (CLC 2006; EEA, 2007), agriculture is the main land use in Italy, covering 51.8% of the territory, closely followed by forested areas (40.2%). Artificial surfaces occupy about 5% of the territory.

National fire data were obtained for the period 1985-2008 from two sources of data, the European Fire Database (EFD) from the Joint Research Center (JRC) and the Sardinian Forestry Corp (CFVA, Corpo Forestale e di Vigilanza Ambientale della Regione Sardegna) database. The EFD is the largest repository of information on individual fire events in Europe (Camia *et al*., 2010). The database summarizes, on a monthly basis, the number of fire events and the total burned area of a given NUTS (Nomenclature of Territorial Units for Statistics) 3 unit (administrative level of province). A preliminary analysis of the EFD database revealed a data gap for Sardinia Region from 1985 up to 1997, so the CFVA fire daily database was used instead for the whole study period.

The weather data were obtained from the interpolated (25x25 km) daily meteorological database developed in the framework of "Monitoring of Agriculture with Remote Sensing" (MARS) project. The database was created using different weather data sources such as direct observations from meteorological stations, and from remote sensing platforms. The dataset, comprising the time period 1985-2008, consists of daily value of air temperature, precipitation, wind speed, and vapour pressure.

Since relative humidity data were not available in the MARS database, we estimated it from the air temperature, vapour pressure, and the dew point temperature (Snyder and Show, 1984).
Finally, fire and weather datasets were aggregated in a database at 25 km resolution grid and on a monthly basis using ArcGIS 9.3 ©-ESRI.

2.2. Fire danger indexes and statistical analyses

Fire danger was calculated through the Canadian forest Fire Weather Index System (FWI), which provides a rating of fire danger through fuel moisture and fire behaviour potential (Van Wagner, 1987). The FWI is composed by 6 sub-codes, the first 3 rating fuel moisture content of the forest floor layers and the other 3 the potential fire behaviour. The Fine Fuel Moisture Code (FFMC) rates the moisture of litter and other dead fine fuels at the top of the surface fuel layer; Duff Moisture Code (DMC) embodies the moisture content of loosely compacted, decomposing organic matter weighing about 5 kg m^{-2}, when dried (this is an indicator of fuel consumption in moderate duff layers and medium-sized woody material (Carvalho 2010)); and the Drought Code (DC) represents the moisture content of the deep layer of compact organic matter.
As outlined above, the other 3 sub-codes estimate the potential fire behaviour, combining the previous fuel moisture codes and weather. The Initial Spread Index (ISI), obtained by the combination of wind and the FFMC component, assesses the rate of fire spread without the influence of variable quantities of fuel; the Build Up Index (BUI) combines DMC and DC components to represent the total fuel available for combustion; and the final Fire Weather Index (FWI) is the combination of ISI and BUI components and represents the intensity of fire spreading as a rate of energy output per unit of fire front length. As highlighted by Alexander (2008), each individual component of the FWI system is actually a fire danger index, revealing different aspects of fire danger that are difficult to synthesize into one single number.
Usually, the FWI system is computed by daily meteorological variables recorded at noon. In this study, FWI was computed using daily meteorological values from MARS database as proxy of instantaneous values at 12:00. After the FWI system calculation, the dataset comprised daily values for all the 565 cells derived from the MARS dataset and for the whole 24-year period.
To handle this amount of data, a preliminary hierarchical cluster analysis, based on the fire/weather dataset, was performed to identify homogeneous areas in terms of fire occurrence and climate (pyro-climatic areas) (Bacciu *et al*., 2014) (Figure 1). The Mann-Kendall non-parametric statistical test was thus applied to evaluate the existence of trends on fire danger components and weather data series. As commented by Wastl *et al*. (2012), a shift in fire danger might be induced by an increase of either absolute index values or number of days with elevated index values. We thus calculated the number of days, for each year and pyro-climatic area, exceeding the threshold of the FWI 95^{th} percentile of the whole time period. Then we proceeded with the Mann-Kendall non-parametric statistical test over the past 24 years to investigate on the eventual increase of fire extreme days. Mann-Kendall test was performed using an Excel macro named MAKESENS created by Salmi *et al*. (2002).
Finally, historical fire activity was analysed in relation to monthly averages of FWI system components to understand the relationships among variables and to develop statistical models to be used to project fire activity in the near future. Separate analyses were carried out at cluster level and a classical stepwise Multiple Linear Regression analysis was applied for the period 1985-1999 (training dataset). The Multiple Linear Regression is one of the most common methods applied to analyse relationships between fire activity and fire danger/weather parameters (e.g. Carvalho *et al*., 2008; Camia and Amatulli, 2009; Bacciu *et al*., 2014). The stepwise approach combines entry and removal of regression terms, which were accepted or discharged as long as they meet significance criteria. The natural logarithm was used to normalise burned area and fire number for the normality requirement, as it is a common procedure followed in other modelling works (Carvalho *et al*., 2008; Amatulli *et al*., 2013). The 9-year period 2000-2008 was then used as external validation dataset. The performances

of the model equations were evaluated using the R^2 coefficient of determination between estimated and measured values.

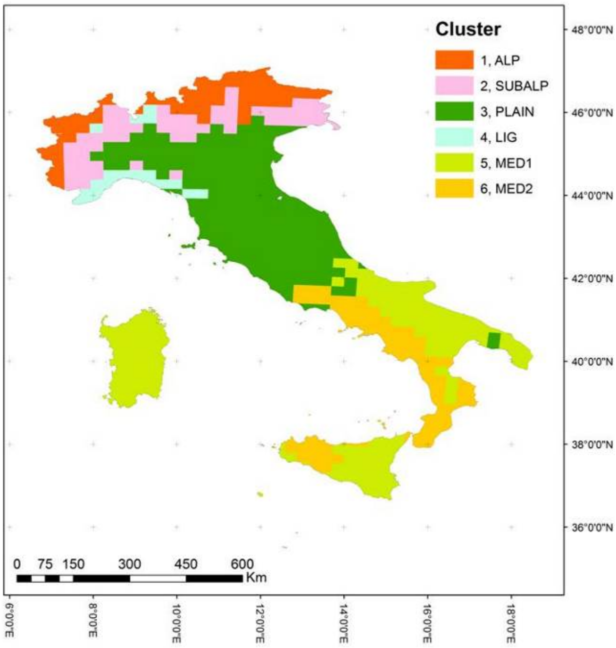

Figure 1. Map of pyro-climatic regions in Italy (from Bacciu et al., 2014)

3. Results

The descriptive statistic of the fire-regime metrics at cluster level is shown in Table 1. The most fire-prone zones are located in the Southern clusters (MED1 and MED2) although a marked fire activity also occurred in LIG (19% burned area over total, 2 fires km^{-2}). From 1985 to 2008, about 2.5 million of hectares were burned (~10% over the Italian total area), about 230,000 fire ignitions occurred, and the annual average burned area was ~100,000 ha. The maximum recorded area burned was in 1993 and 2007 (9.2% and 9.1% over the total, respectively). High level of inter-annual variability of burned area (computed through the coefficient of variation, cv) was found in Northern clusters (ALP and SUBALP) with low fire activity (0.2-0.4 fires km^{-2}), suggesting a stronger influence by weather and climate. As expected, clusters with marked Mediterranean climate and significant fire activity (i.e. Sardinia, Calabria, and Sicily, which had the highest area burned values and number of occurrences in Italy) showed a low inter-annual variability in both fire number and burned area, probably due to persistent human activities.

Five-year averages of maximum and minimum temperatures as well as precipitation and relative humidity are displayed in Figure 2 for each pyro-climatic area. The Mann-Kendall trend test highlighted a generalized significant positive pattern for air temperature variables in all clusters (overall almost 0.5°C and 0.7°C per decade for maximum and minimum temperature, respectively). On the other hand, annual precipitation trends were not significant and the signs of the slopes were different across areas, while on the contrary relative humidity showed overall a significant negative pattern.

Table 1. Number of fire (FN) and burned area (BA) statistics at cluster scales, for the period 1985-2008. CV is the coefficient of variation

CLUSTER	CODE	FN (*1000)	BA (ha*1000)	% BURNED OVER TOTAL	FIRE DENSITY (FN km^{-2})	AVG FIRE SIZE (ha)	CV FN	CV BA	FIRE SEASON (Month)
Cluster 1	ALP	6,2	62,0	1,99	0,20	9,97	0,49	1,22	12,1,2,3
Cluster 2	SUBALP	13,8	147,5	4,27	0,40	10,66	0,46	1,20	12,1,2,3
Cluster 3	PLAIN	37,2	279,1	2,62	0,35	7,50	0,47	0,77	7,8,9
Cluster 4	LIG	21,4	193,9	19,00	2,10	9,06	0,52	0,76	12,1,2,3, 8
Cluster 5	MED1	89,8	1109,9	13,90	1,12	12,36	0,38	0,60	6,7,8,9
Cluster 6	MED2	64,4	669,4	16,90	1,63	10,40	0,41	0,66	6,7,8,9

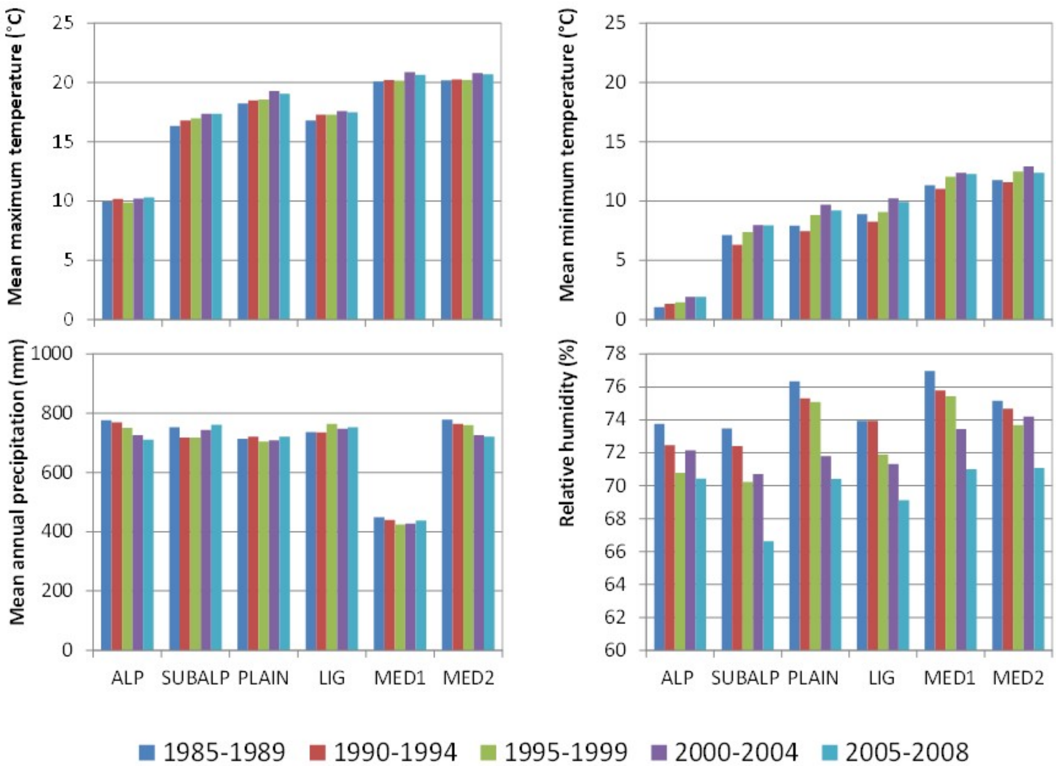

Figure 1. Evolution of mean maximum and minimum temperature, annual precipitation and relative humidity on a five-year basis (1985-1989, 1990-1994, 1995-1999, 2000-2004-2005-2008) in pyro-climatic areas

Overall, the statistical analysis of the mean forest fire danger index values (Table 2) revealed few significant changes during the 24 year of analysis. According to the Mann-Kendall trend test, there was a significant downward trend ($p<0.01$) in DC for ALP cluster, and a significant upward trend in four out to six cluster in ISI index. The number of days with exceptionally high meteorological fire danger was assessed calculating the annual number of days above the 95th percentile threshold. The analysis showed overall a statistically significant increase during the analyzed period, ranging from 1 to 8 days per decade. Overall, the mean number of extreme fire danger days ranged from 4 in cluster ALP to 30 in cluster MED1. The most important increase in number of extreme fire danger days were recorded in PLAIN and MED1 clusters. Ranging from an average of 22 days in 1985-1996 to 39 days in the period 1997-2008, MED1 exhibited a significant increase of 43%. A stronger increase (65%)

was recorded in SUBALP area, which went through an average of 7 days during the first period to 19 days in the period 1997-2008.

Table 2. Mann-Kendall trend test (Z score) results for mean FWI System components for each pyro-climatic area and mean annual number of days exceeding the FWI 95th percentile of the whole 24-year period.

** p= 0.05; ** p= 0.01; ***p= 0.001*

	Mann-Kendall trend Test Z						Estreme fire danger days	
CLUSTER	FFMC	DC	DMC	ISI	BUI	FWI	1985-1996	1997-2008
ALP	-0,06	-4,69**	-0,21	0,00	-0,39	-0,03	2	4
SUBALP	0,07	-3,29	0,07	0,04**	-0,08	0,02	7	19
PLAIN	0,10	0,02	0,45	0,04**	0,49	0,03	14	32
LIG	0,07	2,24	0,26	0,02*	0,43	0,03	9	24
MED1	0,03	-3,83	0,32	0,04**	0,00	0,02	19	29
MED2	0,08	-0,85	-0,06	0,01	-0,11	0,02	22	39

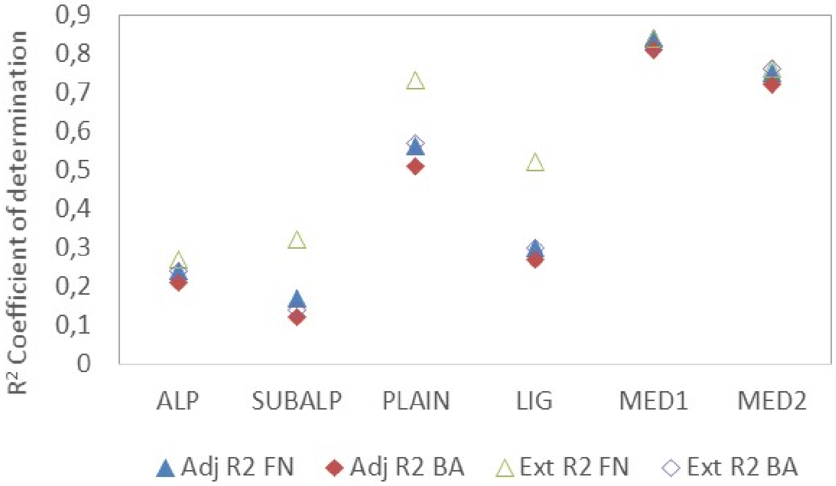

Figure 3. Monthly fire number and burned area explained variance (Adj R^2) and external validation values (Ext R^2)

Coefficients of determination (R^2) resulting from the Multiple Linear Regression analysis of monthly area burned and monthly number of fires considering the whole year for the six clusters across Italy are given in Figure 3. All coefficient were highly significant with $p<0.001$. We also checked for collinearity through the variance inflation factor (VIF). In those cases where predictors entered the final stepwise model and their VIF was higher than the value of 10, thus creating multicollinearity problems (Myers, 1990), we decided to exclude those variables from the regression in order to avoid any further inconsistencies. Finally, an informal analysis of the data using histograms and scatterplots was performed to reveal threats to the assumption of linearity of residuals of the dependent variable (data not shown).

The explained variance ranged from 17 to 84% for fire number and from 12 to 71% for burned area. Clusters in northern and central regions showed the lowest variances, accounting from 17% up to 56% for fire number and from 12% to 51% for burned area in cluster SUBALP and in cluster PLAIN, respectively. On the other hand, pyro-climatic areas in southern regions exhibited variances above 70%, for both fire number and burned area. The external validation R^2 values (period 2000-2008) are slightly bigger than the internal validation.

4. Discussion and conclusion

In this study, we investigated recent trends in both climate and fire danger parameters and we highlighted the relationships between the FWI System components and fire activity in the 6 pyro-climatic areas identified by Bacciu *et al*. (2014).

As a first analysis, we applied the non parametric Mann-Kendall test to assess the statistical significance of weather and fire danger trends. The results of our study indicated the overall increase of temperatures, highlighting that the warming did not have homogeneous impacts all over the country, corroborating other findings over the past decades in Italy and in other areas of the Mediterranean Basin (e.g., Brunet *et al*., 2007; del Rio *et al*., 2012; Koutsias *et al*., 2012). Furthermore, annual precipitation records presented an unclear trend, except in the Alpine area. This data is consistent with the findings of Wastl *et al*. (2012), which reported for this area a slight increase of about 8% in annual precipitation. Moreover, our results highlighted a dichotomy in signs that seems to be in agreement with the results of other researchers.

Generally, the slope of the mean annual fire danger was positive at nearly every cluster, statistically significant in MED1. The situation in ALP cluster, as revealed by the weather variables, was the opposite with a statistically significant downward trend in mean values, probably influenced by the increase in total precipitation. The first results are in agreement with Moriondo *et al*. (2006), who found an increase in mean fire danger in the Mediterranean Basin. On the other hand, the clear decrease of the danger in ALP pyro-climatic area is in contrast with findings reported by Wastl *et al*. (2012) that showed a general increase of fire danger despite this trend was highly variable in consideration of the spatial and the time scale. The wide-ranging positive trend in fire danger corresponded also to a general increase in the frequency of extreme fire danger events. The analysis of the annual number of days above the 95th percentile threshold showed that although southern clusters were characterized by a high number of extreme fire danger days, considerable increment occurred also in northern and central clusters.

Finally, by modelling both fire number and burned area on the basis of monthly FWI components in the different clusters, this study contributes to the understanding of the relationships between fire activity and fire danger indices. Although the study area presented a generalized decrease in both fire number and burned area for the period 1985-2005 (Spano *et al*., 2014; Bacciu *et al*., 2014), the multiple regression analysis showed that FWI system components (especially FFMC and ISI) are good predictors, especially for the clusters with summer fires. Similarly, Amatulli *et al*. (2013) highlighted the drought code (DC) and the initial spread index (ISI) as predictors consistently selected in the equations using the Multiple Linear Regression approach. Results achieved by Carvalho *et al*. (2008) in Portugal revealed that FWI mean and maximum values contributed to explain a great part of the variance in burned area.

Although fire activity in Italy is influenced by a number of factors not related, as fire danger, to weather conditions, the simple statistical models developed in this work can reproduce an important part of the inter-annual fire variability. Thus, the identified relationships could be incorporated in predictive models of fire risk and short- and long-term fire planning strategies that, in turn, could be boosted by the enhancement and a wider use of long-range climate outlooks (such as the seasonal and decadal predictions, e.g. Borrelli *et al*. (2012); Bellucci *et al*. (2014)). Furthermore, the developed models could be used as inputs for the construction of future fire scenarios (e.g., Amatulli *et al*., 2013) to understand the future magnitude of the issue and thus to develop new fire risk mitigation strategies.

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