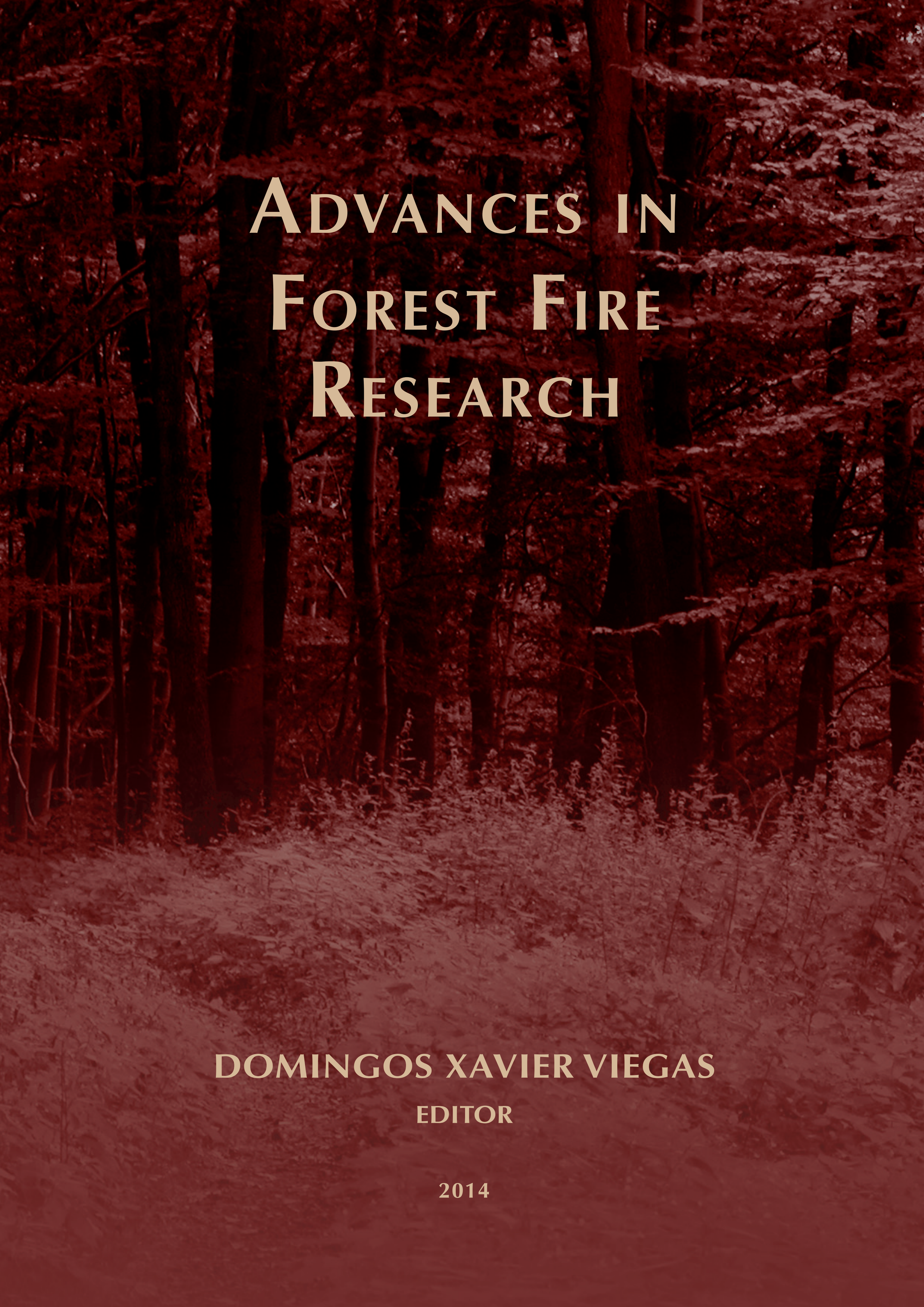

ADVANCES IN FOREST FIRE RESEARCH

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Impacts of climate change on the fire regime in Portugal

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Abstract

Wildfires in Portugal are a major problem, with about 18 500 fires and 110 000 ha burnt every year and an increasing trend of the large fires (>100 ha) during the 1980 – 2011 period. In previous studies, climate and weather conditions were identified as the most important drivers of annual total burnt area in the country which inspire assessing potential changes in the statistical distribution of the areas burnt by fires in the expected warmer and drier conditions of future climate. The aim of the study is therefore to project area burnt by vegetation fires in Portugal for different future climate scenarios using an appropriate Burnt Area Model (BAM). The BAM is a multiple regression model that shown to be able to simulate the burnt areas in July and August with just two predictors: the Daily Severe Rating (DSR) in the pre-fire season (May and June) and during the fire season (July and August). Then, the regression model is fed with simulated data by a Global Climate Model (GCM) respecting to present climate and to future IPCC emission scenarios B1 and A1B. It is shown that samples of observed and simulated logarithms of burnt areas follow normal distributions. Changes in measures of location and dispersion (mean and variance), from recent past to future climates, are analysed after statistically removing the effects due to the limitations of the GCM and the BAM. When comparing present climate with future climate scenario B1 (A1B), maximum increases in the averages of the decimal logarithm of July and August burnt area are of 11% (28%) while the standard deviation remaining almost unchanged for scenario B1 and presenting an increase of 25% for A1B. Obtained estimates need to be looked at with due care but the developed approach consistently points towards an increasing risk of fire under future climate conditions, inter-annual variability and likelihood of having much larger fire events.

Keywords: *Forest fire; Climate change; GCM; Fire risk/danger*

1. Introduction

Assessing the potential impacts of climate change on the fire regime is especially relevant in Portugal, where according to the Portuguese National Forest Authority (*Instituto de Conservação da Natureza e das Florestas*, ICNF) and the European Forest Fire Information System (EFFIS), more 610 000 fires and 3,5 million ha have burnt between 1980 and 2012, almost 1 million ha of which between 2003 and 2005 (Calado and Dacamara 2008). Besides, the number of large fires (with more than 100 ha), amount of burnt area (hereafter, BA) and fire severity have lately increased in Portugal (Pereira *et al.* 2011). Weather and climate are considered the most important drivers of fire activity, even more important than fuel pattern and topography in determining BA in simulated landscapes due to the direct and indirect profound influence they have on wild land fire ignition potential, fire behaviour and severity (Cary and Banks 2000; Benson *et al.* 2008). The climatic conditions determine the existence, type and life cycle of the vegetation which helps explaining the strong resemblance between the spatial patterns of the global pyrogeography (Krawchuk *et al.* 2009) and the updated world map of the Köppen-Geiger climate classification (Peel *et al.* 2007). On the other hand, weather conditions such as lightning promotes fire ignition, while air temperature, wind, atmospheric stability and air relative humidity determine the fuel moisture content and fire spread and, on the contrary, precipitation, even in small amounts, contributes to fire extinction (Pereira *et al.* 2013).

Climate and weather play a particularly important role in the fire regime in Portugal, where long-term climatic pre-conditions (e.g. temperature and precipitation in winter and spring before the summer fire peak season) and short-term synoptic forcing (e.g. extreme synoptic weather patterns and weather types from classifications schemes) are able to explain about two thirds of the variance in the annual, seasonal and monthly total BA (Pereira *et al.* 2005; Pereira *et al.* 2013; Trigo *et al.* 2013). Extreme fire activity as recorded in 2003 and 2005 tends to occur under (also) extreme and consistent weather conditions from the surface to high levels of the atmosphere (Trigo *et al.* 2006) and is related to the evolution of the synoptic- and meso-scale wind, temperature and humidity patterns associated to the appearance of the Iberian thermal low (Hoinka *et al.* 2009).

These factors are continuously changing due to natural climate variability and human-caused climate change (Stocker *et al.* 2013) which may contribute to the high inter-annual variability and increasing trends observed in the last decades (Pereira *et al.* 2005; Pereira *et al.* 2011) and legitimizes the ambition to try to estimate future fire activity.

Many of the most recent studies on the impacts of climate change on some aspect of the fire regime and wildfires has focus on North (Johnstone *et al.* 2010; Wotton *et al.* 2010; Westerling *et al.* 2011; Rocca *et al.* 2014) and South America (Silvestrini *et al.* 2011), Australia (Pitman *et al.* 2007; Murphy and Timbal 2008; Clarke *et al.* 2011) Lynch *et al.*, 2007), in boreal forests of North America and Eurasia (Kilpeläinen *et al.* 2010; Liu *et al.* 2012; De Groot *et al.* 2013), in Europe (Moriondo *et al.* 2006; Batllori *et al.* 2013; Cane *et al.* 2013; Bedia *et al.* 2014; Karali *et al.* 2014) and even at global scale (Moritz *et al.* 2012). However, and despite the magnitude of the problem in Portugal, a very short list of studies have dealt with the impact of climate change on wildfire risk in Portugal (Durão and Corte-Real 2006; Carvalho *et al.* 2008; Carvalho *et al.* 2010; Pereira *et al.* 2013).

The projection of future fire activity requires the development of robust and resistant fire-vegetation-weather/climate relationships to be used in future climate conditions and the availability of sufficiently long and reliable datasets of observed and simulated values of meteorological and fire variables (Pereira *et al.* 2013). Portugal holds one of the largest (in terms of total number of recorded fires) and most comprehensive rural fire databases, not only in European context but also in comparison to many other countries worldwide (Pereira *et al.* 2011).

Currently, a large set of long and reliable meteorological datasets of analysis and reanalysis are available for climate research studies which includes the European Centre for Medium-Range Weather Forecasts (ECMWF) ECMWF 40-year Reanalysis (ERA-40), the ECMWF Interim Reanalysis (ERA-Interim), the Japanese 25-year (JRA-25) and 55-year Reanalysis (JRA-55), the NASA Modern Era Reanalysis for Research and Applications (MERRA) and (MERRA2), the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) and NCEP/DOE Reanalysis II and the NOAA-CIRES 20th Century Reanalysis V2.

On the other hand, General Circulation Models (GCMs) are nowadays recognized as suitable tools for climate modelling because they are based on well-established physical principles, able to simulate global- and many regional-scale observed features of contemporary climate, past climate changes and there is significant confidence that GCM provide credible quantitative estimates of future climate change (Randall and Fichefet 2007). In this sense, most climate models are able to derive fire danger and thereby characterize a probable fire regime (Lynch *et al.* 2007). In addition, climate change data, which may include climate estimates from observations, socio-economic data and scenarios, global climate model data simulated by different GCM and for different future climate scenarios may be easily obtained from many different data providers such as the Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC) or the Program for Climate Model Diagnosis and Intercomparison which provides the World Climate Research Programme Coupled Model Intercomparison Project, WCRP CMIP datasets (Meehl *et al.* 2007). Recently, a Burnt Area Model (BAM) was developed for Portugal based on multiple regression analysis of meteorological parameters with the aim to model the BA during the summer months and be used as a BA generator (Pereira *et al.*

2013). Therefore, the aim of this study is to produce and compare projections of future BA in Portugal by means of the BAM for different future climate change scenarios.

2. Materials and Methods

This study is based on a fire database and on daily meteorological data of both analysed and simulated fields. Indices of fire risk that integrate the Canadian Forest Fire Danger Rating System (CFFDRS) are then computed using the appropriate meteorological data.

2.1. **Data**

The fire database was provided by the Institute for the Conservation of Nature and Forestry (*Instituto da Conservação da Natureza e das Florestas*, ICNF) and consist of detailed information (e.g., fire ignition location, in terms of administrative division of Portugal, fire ignition and extinction date and time, fire area in forest, shrublands and agricultural land cover type) obtained from ground measurements for each fire occurred in Continental Portugal between 1980 and 2011. This dataset is an extension of the Portuguese Rural Fire Database (Pereira *et al.* 2011) and after correcting the additional data for inconsistencies and errors using the same procedures, monthly cumulated values were computed for the considered 32 – year period.

The observed meteorological database consist of analysed fields from the ERA-Interim which is the latest global atmospheric reanalysis produced by the ECMWF to replace the ERA-40 with a new atmospheric reanalysis which will extend back to the early part of the twentieth century and able to provide a better representation the hydrological cycle, improve the quality of the stratospheric circulation and the consistency in time of the reanalysed fields (Dee *et al.* 2011). The ERA-Interim data server surface archive has a mixture of analysis fields, forecast fields and fields available from both the analysis and forecast which is determined by the step variable: 0 for analysis (which are available for 0000, 0600, 1200 and 1800 UTC); 3, 6, 9 or 12 for forecast fields which are produced from forecasts beginning at 0000 and 1200 UTC). The other daily archives have only analysis data.

The selected meteorological fields are: 2 meter air temperature, 2 meter dew point temperature, 10 meter zonal and meridional components of wind speed and 24 hour cumulated precipitation (all at 12 UTC). The air relative humidity was computed with the Magnus formula (using 2 meter air temperature, 2 meter dew point temperature) and corrected according to the altitude. All meteorological fields are defined on a 0.75°×0.75° latitude/longitude grid over Continental Portugal. Spatial means were then computed over the selected grid points and monthly means were finally derived for all meteorological data.

The simulated meteorological database consist of outputs from the Model for Interdisciplinary Research on Climate (MIROC), which is a coupled Atmosphere-Ocean GCM that comprises five components, namely atmosphere, land, river, sea ice and ocean. Developers of MIROC are at the Centre for Climate System Research (CCSR), the University of Tokyo, the National Institute for Environmental Studies (NIES) and the Frontier Research Centre for Global Change (FRCGC). Several different model comparison studies identify MIROC as one of the best models (Lucarini *et al.* 2007; Scherrer 2011; Watanabe *et al.* 2011; Watanabe *et al.* 2011; Mochizuki *et al.* 2012; Chikamoto *et al.* 2013) with especial good performance over the Iberian Peninsula (Nieto and Rodríguez-Puebla 2006; Errasti *et al.* 2011).

For comparison purposes, data for three grid points were selected from MIROC 3.2 medres grid, all approximately at the same longitude but at different latitudes: two of them located over Portugal (one in the south and another in the centre) and one at north of Portugal, in Spanish region of Galicia. Daily grid values of 10 m wind speed, 24h cumulated precipitation, surface air temperature and relative humidity were extracted for 1951 – 2000 period respecting to the recent past conditions (20th century) model simulations (20C3M), and for the 2051 – 2100 respecting to IPCC Special Report on Emissions Scenarios (SRES) B1 and A1B (Nakicenovic and Swart 2000). The B1 scenario corresponds to a high level of environmental and social consciousness accompanied by rapid changes in economic structures and the introduction of cleaning technologies. On the other hand, the A1B scenario reflects a future world of very fast economic growth, low population growth, with a rapid introduction of new and more efficient technology, and a balanced mix of technologies and supply sources.

2.2. **The Canadian Forest Fire Weather System**

In this study, the indices of the Canadian Forest Fire Weather Index (FWI) were used to account for the effect of weather on fuels and fire behaviour. The FWI System (Figure 1) comprises six components: the first three components, the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC) and the Drought Code (DC), are fuel moisture codes which aim respectively to rate the moisture content of litter and other fine fuels, the average moisture content of loosely compacted organic layers of moderate depth, and the average moisture content of deep, compact organic layers; the remaining three components, the Initial Spread Index (ISI), the Build Up Index (BUI) and the Fire Weather Index (FWI), are fire behavior indices, which characterize the rate of fire spread, the fuel available for combustion, and the frontal fire intensity (Van Wagner and Pickett 1985; Van Wagner 1987). Finally, the Daily Severity Rating (DSR) is simply a power function of FWI ($DSR = 0.0272 \times FWI^{1.77}$), with the aim to rate the difficulty of controlling fires and specifically designed for averaging either in time or in space in opposition to FWI that is suitable as a single day value. All these indices are computed solely with the values of four meteorological variables and their values increase with the rise of fire danger (Van Wagner and Pickett 1985). The FWI System was developed for Canada but has been successfully used all over the world (Amiro *et al.* 2005; Wotton 2009) and shown to be especially useful in Portugal to assess the fire behaviour potential in maritime pine stands (Palheiro *et al.* 2006) and to rate fire risk in Portugal during the summer season (Rainha *et al.* 2002; Viegas *et al.* 2004; Carvalho *et al.* 2008; Carvalho *et al.* 2010). Since 1998, the System has been operationally used by the Portuguese Weather Service.

Values of the FWI and DSR derived on selected grid points based on daily values of the above-listed meteorological values (analysed and simulated) and then, spatial averages were computed over grid points and monthly means were finally computed.

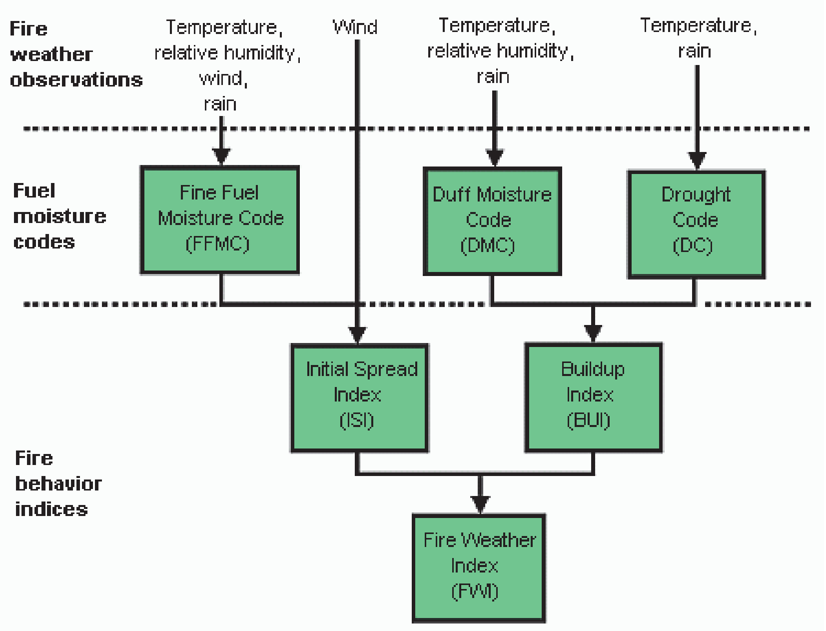

Figure 1. The Structure of the FWI System. The components of the FWI System are computed with consecutive daily observations of air temperature, relative humidity, wind speed, and 24-hour rainfall. The six standard components provide numeric ratings of relative potential for wildland fire. Adapted from Natural Resources Canada (http://cwfis.cfs.nrcan.gc.ca/background/summary/fwi).

3. Results

3.1. The observed summer burnt areas

The annual cycle of monthly BA for Continental Portugal during the considered 32 – year period is shown in Table 1. It is well apparent that the vast majority of area burnt by forest (71% of the total BA) take place during the summer months of July and August. The close agreement between the time series of annual and July plus August BA and the very large inter-annual variability dominated by the outstanding values registered in the years of 2003 and 2005 (Figure 2) suggest that the annual fire regime is dominated by the events that take place in July and August and to restrict the study to those two summer months.

Table 1. Annual cycle of monthly burnt area in Portugal for the period 1980 − 2011. Values of simple and robust and resistant statistics including the maximum, upper quartile (Q3) median, lower quartil (Q1), minimum, interquartile range (IQR), range and total.

Burnt area (ha)

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	1100	3118	14780	11360	3987	18962	99087	261481	66015	27606	9157	3734
Q3	115	513	2161	1447	1074	6197	43856	60237	25123	4548	102	93
Median	34	124	585	352	372	2112	16780	30779	11679	1632	18	17
Q1	10	12	85	109	145	555	7979	18337	6246	479	2	0
Minimum	0	0	3	0	3	27	529	3571	3325	0	0	0
IQR	106	501	2076	1338	929	5643	35877	41900	18877	4069	100	93
Range	1100	3118	14777	11360	3983	18935	98559	257910	62690	27606	9157	3734
Total	4775	14247	67787	36393	21801	140834	845584	1612525	574751	122332	13206	5908
Total (%)	0%	0%	2%	1%	1%	4%	24%	47%	17%	4%	0%	0%

This behaviour is expected in Mediterranean regions since vegetation presents elevated levels of water stress as induced by periods of dry conditions and relatively high temperatures that often characterise the late spring and the beginning of summer (Viegas *et al.* 2001; Pereira *et al.* 2005; Trigo *et al.* 2006). The inter-annual variability (as measured by the inter-quartile range) is also clearly larger during the summer months and it is worth noting that the variability of July and August is about twice the one of September.

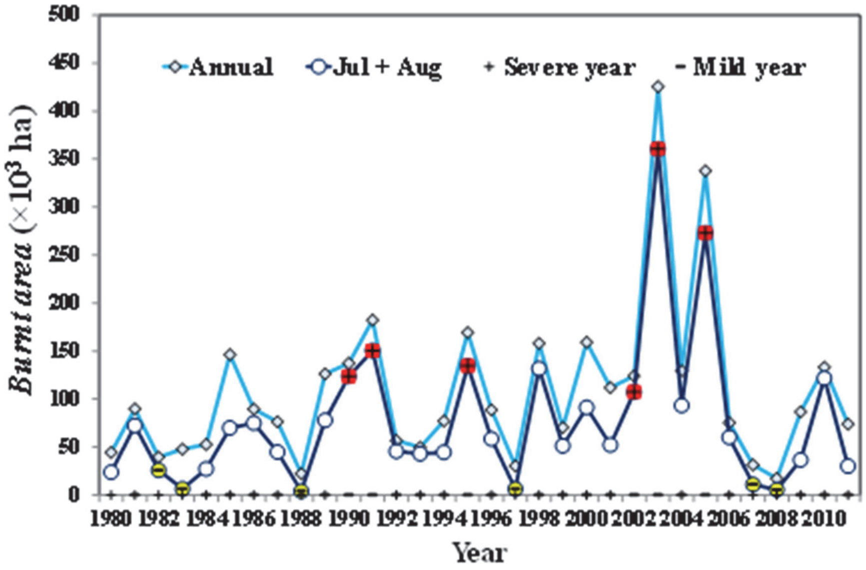

Figure 2. Inter-annual variability of burnt area amounts in Continental Portugal for the whole year (Annual) and just for July + August (Jul + Aug), for the period 1980−2011. Severe (+) and mild (–) years signs inside respective red and yellow circles.

It is also important to underline some of the results of correlation analysis during the period 1980 – 2011, namely: (*i*) the existence of a positive and statistical significant (p-value<0.0001) value of the Pearson Product-Moment correlation coefficient ($r = 0.66$) between the areas burned in July and in August; (*ii*) the very low ($r = 0.22$) and statistically not significant correlation between the DSR monthly means of July and August; (*iii*) despite the significant (p-value<0.0001) high value of the correlation coefficient between DSR and the decimal logarithm of monthly BA for the months of July and August, ($r = 0.76$ and $r = 0.59$, respectively). These results underline the usefulness of the DSR to rate the meteorological fire danger and suggests the existence of a pre-summer season climatological background that would condition the fire regimes of both July and August.

3.2. **The Burnt Area Model**

With the aim of identifying the most promising predictors of BA in July and August and characterizing the climatological background, a composite analysis (Pereira *et al.* 2005; Trigo *et al.* 2006) of all the analysed meteorological fields was performed for two classes of extreme summer fire seasons, respectively severe and mild (Figure 2), defined depending on the monthly BA of July and August are both greater/lesser than the upper/lower tercile of the respective month (i.e. greater than 40,000 ha for July and 46,000 ha for August).

Results reveal that, from the meteorological standpoint, major differences between mild and severe years may be found during the months preceding and during the summer fire season (Figure 3). In the pre fire season, severe years are associated to positive anomalies of precipitation in the early spring (March), which favours the growth of vegetation, followed by significant negative anomalies of precipitation and air relative humidity and positive air temperature anomalies in May and June. This climatic pattern is consistent with the atmospheric circulation from NE, over Portugal during this period and, as expected, the increasing trend of positive DSR anomalies from April to June reflect the above-described cumulative behaviour of temperature, relative humidity, wind and precipitation. During the fire season, major statistically significant differences between severe and mild fire seasons are naturally found in all meteorological variables and, consequently, in DSR. Severe fire seasons are characterised by extreme negative precipitation and humidity anomalies and positive temperature anomalies associated to south-eastern winds leading to utmost DSR anomalies. In the case of mild years, the opposite behaviour is observed.

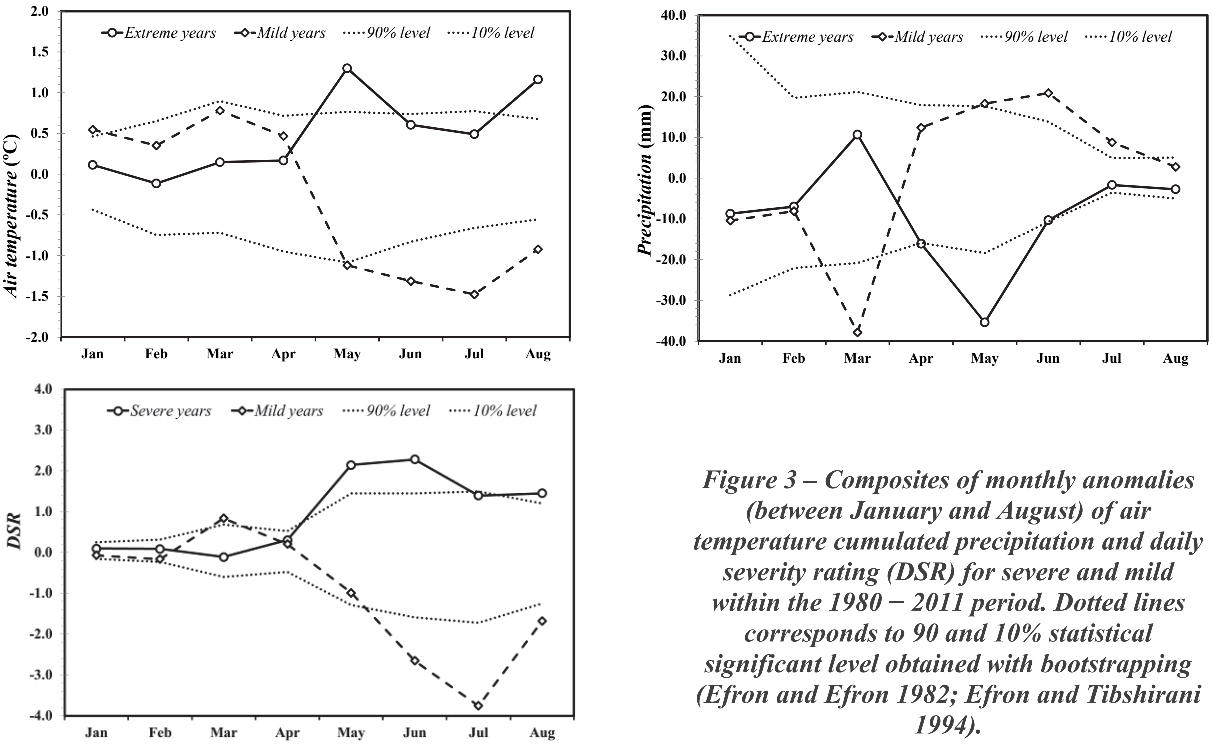

Figure 3 – Composites of monthly anomalies (between January and August) of air temperature cumulated precipitation and daily severity rating (DSR) for severe and mild within the 1980 − 2011 period. Dotted lines corresponds to 90 and 10% statistical significant level obtained with bootstrapping (Efron and Efron 1982; Efron and Tibshirani 1994).

These results suggest the development of a multiple linear regression BAM for decimal logarithm of monthly BA (due to the highly asymmetrical character of monthly BA) in summer months using, as predictors, meteorological variables and/or fire risk indices respecting to the pre-fire and/or fire seasons. In order to mitigate the effects of over fitting, the performance of the experiments was evaluated using a leave-one-out-cross validation scheme (Wilks 2011). Several selection methods (e.g., stepwise, forward, backward and explained variance) using different criteria were tested to select the best and parsimonious BAM for BA time series in July, August and July + August for the 32-year period using the equation presented in Table 2 where the $\mathrm{Log_{10}BA_{J/A}}$ is the decimal logarithm of monthly BA in July or in August; $\mathrm{DSR_{PF}}$ is the monthly mean of DSR during the pre-fire period (PF), defined as May and June when the predictand is the decimal logarithm of monthly BA in July ($\mathrm{Log_{10}BA_{J}}$) and May, June and July when the predictant is the decimal logarithm of monthly BA in August ($\mathrm{Log_{10}BA_{A}}$); $\mathrm{Log_{10}BA_{J/A}}$ is the monthly mean of DSR in July or in August depending if the predictand is the monthly BA in July or August, respectively.

Table 2 – Burnt Area Model regression and ANOVA analysis for July, August, and July + August (1980 − 2011). Statistics includes which includes: regression coefficients (A, B and C) and St. Error, R^2, adjusted R^2 (R^2_{adj}) F-statistic (Regression F) and significance of F (Significance F)

Regression and ANOVA analysis

$$\mathrm{Log_{10}BA_{J/A}} = A + B \times \mathrm{DSR_{J/A}} + C \times \mathrm{DSR_{PF}}$$

	Regression stats		*Coefficients*		*St. error*	*t Stat*	*P-value*
July	***R***	0.78	**A**	2.4952	0.2650	9.4163	0.0000
	R_{adj}	0.75	**B**	0.0973	0.0336	2.8921	0.0072
	St. Error	0.36	**C**	0.1009	0.0233	4.3326	0.0002
					ANOVA		
			df	*SS*	*MS*	*Regression F*	*Significance F*
	Regression		2	5.7904	2.8952	21.9352	1.58E-06
	Residual		29	3.8277	0.1320		
	Total		31	9.6181			
	Regression stats		*Coefficients*		*St. error*	*t Stat*	*P-value*
August	***R***	0.77	**A**	2.4715	0.3104	7.9632	0.0000
	R_{adj}	0.75	**B**	0.1005	0.0295	3.4003	0.0020
	St. Error	0.32	**C**	0.1072	0.0247	4.3353	0.0002
					ANOVA		
			df	*SS*	*MS*	*Regression F*	*Significance F*
	Regression		2	4.4198	2.2099	21.7332	1.71E-06
	Residual		29	2.9488	0.1017		
	Total		31	7.3686			
	Regression stats		*Coefficients*		*St. error*	*t Stat*	*P-value*
July + August	***R***	0.80	**A**	2.4952	0.2650	9.4163	0.0000
	R_{adj}	0.79	**B**	0.0973	0.0336	2.8921	0.0072
	St. Error	0.34	**C**	0.1009	0.0233	4.3326	0.0002
					ANOVA		
			df	*SS*	*MS*	*Regression F*	*Significance F*
	Regression		2	11.7115	5.8557	52.2081	6.11E-14
	Residual		61	6.8419	0.1122		
	Total		63	18.5533			

Results of the regression analysis and analysis of variance (ANOVA) obtained independently for July and August (Table 2) are very similar for both months not only in what respects to regressions statistics (R^2 = 0.59 – 0.61, R^2_{adj} = 0.56 and standard error of 0.32 (August) – 0.36 (July), respectively), regression coefficients (A, B and C), statistical significance (Student's *t* distribution statistic and significance of *F-statistic*). Results for BA in July and August (jointly) are even slightly better (R^2 = 0.64, R^2_{adj} = 0.62) but regression coefficients are very similar to those obtained independently for July and August.

The two predictors are statistically significant and were selected in the same order they appear in the equation, with increasing R^2 value from 0.44, when $\mathrm{Log_{10}BA_{J/A}}$ is the only predictor, to 0.630 when the model has both predictors. Several other aspects are worth being noted namely: the overall good agreement between observed and modelled values of the decimal logarithm of BA; the relatively high value of the coefficient of determination R^2 = 0.64 (p-value<0.001) for July and August BA; which means that the BAM is able to explain, in cross-validation mode, almost 3/5 of the total variance. Finally, the normality of the values of the logarithm of the values of BA observed, modelled and residuals from the use of the BAM was confirmed by the Kolmogorov-Smirnov test. All these features are especially important and will be exploited in the next subsection when the BAM will be used as a generator of monthly BA scenarios in recent past and future climate conditions.

3.3. **The simulated summer burnt areas**

Simulated time series of BA in July and August were generated by feeding the BAM with DSR values computed for the pre-fire period and for the fire season with GCM outputs respecting to present (20C3M) and to future B1 and A1B climate scenarios. The Kolmogorov-Smirnov (K-S) test was used to check that the simulated BA for all cases are normally distributed at the 5% significant level (Table 3). Values of the mean and standard deviations of $\mathrm{Log_{10}BA_{J/A}}$ reveal that, as expected, the use of the multiple linear models with observed DSR leads to a simulated BA samples with the same mean as the one of the observed sample but with smaller variance. However, when feeding the BAM with

Table 3 – Mean, standard deviation (SD) and p-value of the one-sample Kolmogorov-Smirnov test for normality of burnt area time series for July and August observed and simulated by the BAM when fed with ERA-Interim (Modelled) and with GCM outputs (BAM+MIROC) for different periods of scenario B1 and A1B.

Model	Scenario	Period	Mean	SD	p
BAM	Observed	1980 - 2011	4.31	0.54	0.41
	Modelled	1980 - 2011	4.31	0.43	0.85
BAM + MIROC	20C3M	1971 - 2000	5.06	1.06	0.42
	B1	2051 - 2080	5.63	0.72	0.38
		2071 - 2100	6.03	1.07	0.68
	A1B	2051 - 2080	6.72	0.97	0.68
		2071 - 2100	7.48	1.36	0.29

simulated data by a GCM for future climate scenarios there is an increase in both the mean and the variance, even for the recent past conditions (20C3M). The latter case is an expected consequence of the GCM's characteristics, namely the known fact that the simulated meteorological fields by MIROC, or by other climate models, are biased and have too much variability. Accordingly, changes in the mean and in the standard deviation are due to climate change (signal) and to the limitations of BAM and GCM (noise) to properly reproduce the observed reality. With the aim of, at least reduce the model bias, the $Log_{10}BA_{J/A}$ obtained for the recent past conditions (20C3M scenario) were corrected to have mean and standard deviation equal to the observed values. Then, time series of $Log_{10}BA_{J/A}$ for the future scenarios were transformed with exactly the same correction factors.

Comparison between future projections of the normal distributions may be performed on the basis of the descriptive statistics of the decimal logarithm of BA (Table 4). When compared with the present climate scenario (20C3M), there are increases in the means of $Log_{10}BA$ for both future climate scenarios periods, respectively of 7% and 11% (20% and 29%) from the 20C3M to the 2051 – 2080 and 2071 – 2100 periods of the B1 (A1B) scenario. The standard deviation remains almost unchanged from the 20C3M to the last (first) period of B1 (A1B) scenario, but presents a decrease (increase) of about 32% (28%) from the 20C3M to the first 30-year of B1 (A1B) scenario. It is also worth noting that differences in percentiles changes with increasing percentiles, e.g. from 0.39 (0.36) in P5 to 0.48 (0.57) in P50 and to -0.28 (0.38) in P95 when going from present climate to first (last) 30-year period of B1 scenario while the correspondent differences for A1B scenario are even higher (about the double). This is an important aspect, since it reveals that in the B1 scenario conditions, for the 2051 – 2080 period major increases in burnt area are only expected for values below P75 and the larger increases should be expected for P10 (0.58) values of burnt area while for the 2071 – 2100 period the increases are therefore to be expected for all values of burnt area nonetheless larger increases are found between P10 (0.55) and P75 (0.47). A similar changing pattern is expected for A1B scenario during the first period but increasing changes may be expected from P5 (0.85) to P95 (1.47). As expected, differences are even more impressive when analysing changes in BA (and not in the logarithm) from present to future climate scenarios. The median may change from 16,000 ha in 20C3M scenario to 49,000 ha (158,000 ha) and 61,000 ha (294,000 ha), respectively in the first and second 30-year period of B1 (A1B) scenario. On the other hand, the mean remains unchanged from recent past climate scenario to 2051 – 2080 period of B1 but increase to 158,000 ha in the 2071 – 2100 period of future scenario. Values of the mean BA for A1B scenario are even higher (270,000 and 1,500,000 ha).

Table 4 – Descriptive statistics of corrected log-normal distributions of monthly burnt area for present (20C3M) and future (B1 and A1B) climate scenarios. P: percentiles, IQR: inter-quartile range, RD: Relative dispersion.

	20C3M	B1		A1B	
	1971-2000	2051-2080	2071-2100	2051-2080	2071-2100
Mean	4.31	4.60	4.80	5.16	5.54
SD	0.54	0.37	0.54	0.49	0.69
P5	3.60	3.99	3.96	4.35	4.46
P10	3.65	4.23	4.20	4.55	4.65
P25	3.94	4.43	4.44	4.79	5.14
P50	4.21	4.69	4.79	5.20	5.47
P75	4.63	4.85	5.11	5.48	5.89
P90	5.20	5.01	5.48	5.68	6.41
P95	5.36	5.08	5.75	5.94	6.83
IQR	0.69	0.43	0.66	0.69	0.76
RD	0.08	0.05	0.07	0.07	0.07

4. Conclusions

This study shown that the annual total BA in Continental Portugal is dominated by the fire events taking place in July and August which accounts for almost 3/4 of the total burnt area. The influence of weather conditions on the BA in these summer months was disclosed by the results of composite analysis of relevant meteorological variables performed for severe and mild years, defined as those where both the monthly BA of July and August are higher or lower than the respective upper or lower terciles, respectively. Results indicated that severe years are related to averaged anomalies of precipitation in March followed by positive anomalies of temperature and negative anomalies of precipitation and relative humidity in pre fire season. These climatic patterns are consistent with the atmospheric circulation over Portugal and with the anomalies of DSR becoming increasingly positive and statistically significant from May to June for severe years. Differences were also obtained during the fire season (July and August), where extreme meaningful positive anomalies of temperature and DSR (i.e., above the 90% significant level) were found for severe and negative for mild year composites.

These differences in the meteorological parameters have a profound impact on the life cycle and the thermal and hydric stress of the vegetation. In fact, during severe years a higher averaged precipitation and relative humidity in March increases the likelihood of a healthy growth of vegetation while the lower values of precipitation that follow in May and June, together with the higher values of temperature, increase the stress in a more abundant vegetation contributing to a larger amount of available fuels and burnt area. This process is particularly highlighted if, during the fire season, Portugal is affected by atmospheric circulation patterns that induce extreme hot and dry spells (heat waves) over the territory.

A Burnt Area Model (BAM) was developed to simulate the decimal logarithm of monthly burnt areas in July and August using, as predictors, the DSR during the pre-fire and the fire season. This model is able to explain almost 2/3 of the total observed variance and is almost unaffected by over fitting which increase the confidence in their use in practice with future unknown validation dataset. The BAM was then fed with simulated data by the MIROC climate model respecting to present climate conditions (20C3M) and to future climate IPCC emission scenario B1 and A1B and the bias of the BAM and GCM was corrected before proper comparison between projections of future BA.

When compared with the recent past climate scenario (20C3M) with the two periods (2051 – 2080 and 2071 – 2100) of future climate scenarios B1 and A1B, increases in the means of the logarithm of July and August BA ranges, respectively between 7% and 11% for B1 and between 20% and 29% for A1B whereas the standard deviation remained almost unchanged in the latter case of scenario B1, presented a decrease of about 30% and 9% in the case of the former period of both B1 and A1B and an increase of 28% in the last period of A1B scenario. Differences in percentiles (between present and future climate scenarios) increased with increasing percentiles indicating that the larger increases in burnt area are to be expected for all fire events at the end of the XXI century.

It is very likely that the simulated BA are overestimated due, at least to three orders of reasons: (*i*) the use of global (GCM) or regional (RCM) circulation models (which are just limited representations of the observed reality); (*ii*) the use of a linear BAM (which prevents the existence of feedback mechanisms that might reduce the amounts of burnt area); and, (*iii*) not taking into account other important factors for fire occurrence and size such as those related to changes in fuel structure (Pausas and Paula 2012; Gibson *et al.* 2014); climate-vegetation dynamics and conservation planning (Krawchuk *et al.* 2009); patterns of lightning strikes (Wotton *et al.* 2010; Wendler *et al.* 2011; Liu *et al.* 2012); and anthropogenic activities and drivers of fire, such as control over ignition, fire management, suppression activities, land use/land cover changes (Krawchuk *et al.* 2009; Le Page *et al.* 2010; Aldersley *et al.* 2011; Costa *et al.* 2011; Kloster *et al.* 2012). Nevertheless, obtained results are of the same order of magnitude of other similar studies (Le Goff *et al.* 2009; Carvalho *et al.* 2010; Westerling *et al.* 2011; Nitschke and Innes 2013).

Finally, despite all the identified limitations, the developed approach consistently points towards an increasing of: (*i*) the meteorological fire danger; (*ii*) having much larger fire events; (*iii*) inter-annual variability of the fire regime under future climate, which together with the positive bias will have dramatic consequences at the social, economic and environmental levels. These conclusions could be even more dramatic as an increase of the fire season length is very likely to be expected in boreal and temperate climates (Flannigan *et al.* 2009; Wotton *et al.* 2010; Carvalho *et al.* 2011; Westerling *et al.* 2011; Kloster *et al.* 2012).

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