ASSESSMENT OF CLIMATE-FOREST PATTERN EFFECTS ON FIRE RISK OVER BULGARIA BY USING MSG DATA

Julia S. Stoyanova

National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences
Tsarigradsko chaussee 66, Sofia, Bulgaria

Abstract

Although humans are often the primary cause for fire occurrence, fuel types, moisture, and distribution– vertically and horizontally, are very important for fire ignition and spread. Accounting that fuel moisture couples fire to climate as the fuel loads accumulate according to forest structure and composition at the specific climate conditions, the aim of this study is to examine the relation of climate, fire and forest pattern across a range of environmental conditions and vegetation types on a regional scale. To derive the forest fire regimes and link fire activity to specific fuel moistening/load, the Plant Functional Types /PFTs/ concept in comparative analyses with data from LSA SAF Fire Radiative Power /FRP/ product is applied. Regional PFTs classification according to a Bulgarian static equilibrium scheme of bioclimate (Stoyanova, 2007) is explored. The study is performed by using data for years of relatively 'high'/moderate'/'low' fire activity (2012/2011/2010 correspondingly) and referred to the region of South-Southeastern Bulgaria, Eastern Mediterranean. In parallel, the functioning and structure of corresponding regional forest-PFTs are characterized by the LSA SAF ET, LST and FVC products. Results provide a first step in ranking of natural forest cover regarding susceptibility to fire ignition and spread. Such an approach can provide knowledge towards fundamental understanding vulnerability of land systems to fire on a regional scale in support to forest management and policy.

INTRODUCTION:

Fire danger can be considered as the combination of a large number of factors related to both the probability of fire ignition (human factors, fuel moisture content, fuel flammability, etc.) and potential fire behavior in space and time (terrain conditions, fuel characteristics and load, and weather factors). Land cover controls fire propagation, in interaction with weather. Meanwhile, land cover state is controlled by both climate and land use. Different land covers have widely differing flammabilities depending on species composition, stand age and density, microclimate, and soil conditions (Lavorel et al., 2007). Forest fire is a primary process that influences the vegetation composition and structure of any given location; fire helps shape the landscape mosaic and influence biogeochemical cycles such as the carbon cycle. Forest structure and composition, now and in the past, is influenced by the fire regime (e.g. Wright and Bailey, 1982) but at the same time vegetation structure and productivity influence the occurrence and magnitude of fires.

Fire has important effects on climate through the global carbon cycle, atmospheric chemistry, and changing terrestrial ecosystems. Combustion of organic matter contributes to atmospheric loading of "greenhouse" gases and can affect carbon sequestration regimes. The influence of anthropogenic ignited fires, which accounts for 90% of all biomass burning (Levine, 2000), may increase with population growth and the added pressure for land and resources.

The fire regime has six components: fire frequency, size, intensity, seasonality, type and severity (Flanningan et al., 2000). The interactions between climate, vegetation and fire regimes are complex and difficult to unravel – particularly under modern conditions when fire regimes are influenced by humans. In order to understand the spatial and temporal global/regional distribution of biomass burning, and ultimately the potential impacts to the biosphere and atmosphere, regular, broad scale monitoring is necessary.

Satellite sensors provide daily observations to detect and analyze fires (Justice et al., 2002) and therefore a great deal of research to characterize fires from remote sensing systems has been performed over the past several decades. Fires release heat energy, which is propagated by conduction, convection, and radiation. Fire radiative energy (FRE), like other types of electromagnetic radiant energy, propagates in space and facilitates fire detection by remote sensing. Advancements in satellite remote sensing technology have enabled actual measurement of FRE from space by the SEVIRI onboard the Meteosat Second Generation geostationary satellite (e.g. Roberts et al., 2005). However, since every observation by these sensors lasts only an instant, what they actually measure is the rate of release of FRE per unit time or Fire Radiative Power (FRP) in MW (Kaufman et al., 1998; Giglio et al., 2003; Wooster et al., 2003). Recent studies have shown that the FRE released by a fire is directly proportional to the biomass consumed as well as the smoke emitted (Ichoku, 2008). Measurement of fire radiative energy (FRE) release rates or power (FRP) from space offers opportunities for characterization of biomass burning and emissions in a quantitative manner. In essence, it has enabled the rating of fires, as well as estimation of regional FRP fluxes, which reflect the relative concentrations of biomass-burning activities.

The aim of the study is to distinguish the fire regimes at different forest type land cover on a regional scale (South-Southeastern part of Bulgaria, Eastern Mediterranean) based on the link between climate and forest pattern, and using capabilities of the SEVIRI LSA SAF FRP product (Govaerts et al., 2010; Wooster et al., 2003). In parallel, space heterogeneity of forests-climate pattern is characterized by the functional and structural properties of corresponding vegetation types (Plant Functional Types, PFTs). as derived by LSA SAF products: Land Surface Temperature, LST, Evapotranspiration, ET and Fraction of Vegetation Cover, FVC (http://landsaf.meteo.pt/).

DEVELOPMENT OF METHODOLOGY:

To assess climate-forest pattern effects on static fire risk and fire occurrence over the south-eastern part of Europe using radiative and space/time capabilities of MSG based information, a methodological approach has been specially designed in order to reflect regional land cover specificity from one side and to use information from geostationary satellites at a distance from the sub-satellite point. Two types of research approaches are involved: modelling of long-term climate-land surface equilibrium coupling and observations from meteorological geostationary satellites MSG in parallel to ground truth observations of forest fires (by the Bulgarian State Forest Agency, SFA) and the description of vegetation species distribution over Bulgaria (according local field experience).

As a background of the study, the following considerations are taken into account:

- Forest response to climate regimes can be well understood accounting for the biogeophysical and biogeochemical cycles coupling.
- Climate-fire-forest system can be described by two controlling factors: fuel moisture and forest productivity (as it affected fuel loads), both of which are strongly influenced by water balance. Climate is coupled to the fire regime directly through fuel moisture and indirectly through fuel loads (that is accumulated according to forest structure and composition at the specific climate conditions and fire extend is affected by species compassion and fuel-bed bulk density (Miller and Urban, 1999).
- Stand spatial heterogeneity in forest cover is aggregated by Plant Functional Types (PPTs) units.
- Here we do not attempt to link weather and fire, however.
- Therefore, effects from weather patterns are not accounted in the LSA SAF FRP product performance.

Bioclimatic modelling:

Different methodologies for land cover classifications (often regarded as synonymous with vegetation classifications) and criteria have been used. Most of the schemes can be referred to three groups as follows: (i) Structure and physiognomy features of plants; (ii) Floristics developed on the basis of plants taxonomic affinities; (iii) Bioclimate schemes (e.g. Holdridge, 1967; Budyko, 1956; Prentice et al., 1992; etc.) based not on actual vegetation, but on the dominant climate regime in that region. The complexity of species diversity can be reduced to a few key plant types advocated to predict the composition and functioning of ecosystems in a changing environment by the PFTs concept (Bonan et al, 2002). Functional units in terrestrial ecosystems are defined as sets of plants exhibiting similar responses to environmental conditions and having similar effects on the dominant ecosystem processes, e.g. exchange of matter and energy between land surface and atmosphere or any other selected parameter of a specific interest.

A. Global vegetation distribution:

Land surface and atmosphere interact by complex feedback processes among soil, vegetation, and atmosphere that establish a dynamic coupled system of biogeophysical and biogeochemical exchanges. One of the reveals of this coupling is the zonality of vegetation distribution.

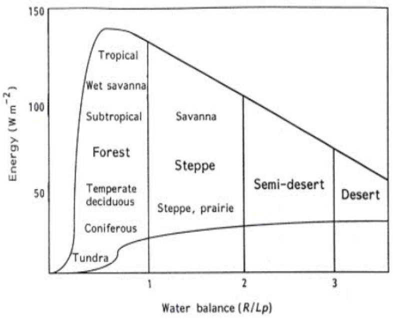

Figure 16.3 The ordination for biogeographical zones as defined by the energy balance (R, W m^{-2}) and the relative dryness index (R/LP, L = the latent heat of evaporation, P = annual precipitation) and the delineations of the major biogeographical zones (Budyko 1986)

Fig. 1. Global vegetation distribution (after Budyko, 1956).

The principle of natural zonality in climate-vegetation processes can be characterized by the universal zonation principle in land-surface natural processes, defined by Dokuchaev (still in 1900) and further adopted by Budyko (1956, etc.). The idea of biogeographycal zonality includes that not only the heat- and water-amounts but their relative proportions are responsible for vegetation distribution. It is framed in a bioclimatological theory, which links climate to major global vegetation zones (biomes) within a bi-dimensional framework and thus describes the various climatic regimes (Fig. 1). This classification is only obvious for broad scale, global vegetation pattern. At a regional/local scale, other environmental (e.g. soil and topography) and historical (e.g. disturbance and succession) factors also strongly influence the vegetation.

B. Regional vegetation distribution:

A zero-dimensional static bioclimatic coupled climate-vegetation equilibrium model for regional land cover classification is developed to simulate the major long-term land-atmosphere exchange processes of matter and energy, as a basis for quantitative description of vegetation distribution. Based on climatological method of Budyko (1956), a conceptual approach for regional application and differentiation of potential natural vegetation cover has been developed.

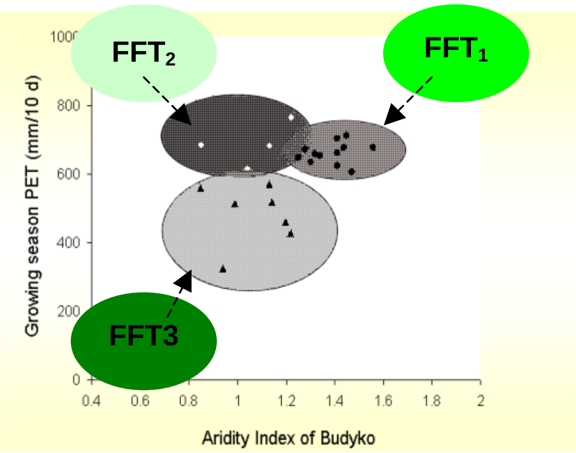

Fig. 2. Plot of dominant Forest Functional Types (FFTs) over SE Bulgaria (Stoyanova, 2007).

It is based on climatological approximations of heat- and water- balances through the potential evapotranspiration of native cover (net radiation estimates) during the growing season $E_0(veg)$ and radiative index of dryness of Budyko β. This is framed in a bi-dimensional biosphere-atmosphere equilibrium scheme (and applied for native forests) that aggregates the forest-cover into functional units, Forest Functional Types (FFTs) and accounts for the regional-scale environmental specific features (climate, relief, forest cover type, and growing season). The model is run for the present-day climate (1961-1990) accounting for land cover of south and southeastern Bulgaria (Eastern Mediterranean) and its functional differentiation (Fig.2), (Stoyanova et al., 2005; Stoyanova, 2007).

The application of the conceptual scheme delineated three functional FFTs units in stable equilibrium with the different climate environment: **FFT1** is situated in the Lower Forest Belt and consists of broadleved xeromesophytes; **FFT2** is also located in the Lower Forest Belt but consists of xerophytes, open deciduous, shrubs. The **FFT3** of native coniferous, evergreen is at the Mid Forest Belt at 1200-1500 m altitude.

Satellite Observation Technology:

Fire Radiative Power as a geophysical variable:

A. Detection and monitoring:

Terrestrial, airborne, and spaceborne remote sensing has long been used to provide data on 'fire counts', essentially by detecting the strong infrared thermal emission signal associated with active fires. Kaufman et al. (1998) introduced the concept of remotely measured fire radiative energy (FRE). As the enhancement proposed was that quantification of the amount of energy radiated during the combustion process could provide a remote measurement related directly to the fire intensity and the amount of vegetation consumed per unit time. Remotely sensed FRE is therefore a candidate for the independent emissions-estimation route called for by Andreae and Merlet (2001) as a result of the biomass burning. This approach is used in the developed LSA SAF Fire Radiative Power Product (FRP) product, which is derived using the Fire Thermal Anomaly (FTA) algorithm for the detection of all "fire pixels" within the image that are believed to contain actively burning fires. The fire detection algorithm implemented for use with SEVIRI is based on the principles used to generate active fire detections within the MODIS fire products fires (Giglio et al., 2003).

B. Radiative energy and fire emissions:

The LSA FRP (MWatts) provides information on the measured radiant heat output of detected fires and is a direct result of the combustion process, whereby carbon-based fuel is oxidised to CO_2 with the release of a certain "heat yield" (Wooster et al., 2003):

$$(C_6H_{10}O_5)n + O_2 + \textbf{\textit{ignition temperature}} \rightarrow CO_2 + H_2O + \textbf{\textit{heat}}$$

FRP calculation relies on the MIR method assuming FRP to be proportional to the difference between the observed fire pixel radiance measured from MSG SEVIRI radiometer and the "background" radiance that would have been observed at the same location in the absence of fire. Resolution for target region of the study, SE Europe is about 5 km for MSG3 Full scanning and time frequency of 15 min. Measuring FRP and integrating it over the lifetime of the fire provides an estimate of the total Fire Radiative Energy (FRE), which for wildfires should be proportional to the total mass of fuel biomass combusted (Wooster et al. 2003; Govaerts et al., 2010).

Geophysical indexes for PFTs identification:

The discriminated regional FFTs (as defined above) are characterised by their functional and structural properties, as seen by MSG satellite information according to LSA SAF products: Evapotranspiration (ET), Land Surface Temperature (LST) and Fraction of Vegetation Cover (FVC), correspondingly.

Experimental design and dataset:

Accounting that fuel moisture couples fire to climate as the fuel loads accumulate according to forest structure and composition at the specific climate conditions, the experimental design is organized towards evaluation the regional pattern of bioclimatic susceptibility to biomass burning, using MSG LSA SAF products, in terms of:

- Characterizing differences in structure/functioning of regional FFTs,
- Characterizing FFTs vulnerability to burning,
- Biomass burning effects for each FFT, comparing FRE released during years of different fire activities (2010 'low', 2011 'moderate', 2012 'high') and corresponding fire-Carbon equivalent emitted are evaluated.

The target region is selected to cover two types of physicogeographycal (Fig. 3a) conditions with a variable climatic aridity (Fig. 3b, Stoyanova et al., 2005). Target region I is located in the Low Forest Belt, covering: plainly/d hilly regions, partially Tracian plain, Tundja hilly plain, Strandja- and Sakar-mountains, South Black Sea coast. Target region II is situated in the Mid Forest Belt: Rhodopes Mountain, at 'Coniferous forest belt', 1200-1500 m alt.

Dataset consists of:

- MSG LSA SAF FRP for 2010, 2011, 2012 available trough EUMETCast and archive data (2010, kindly provided by LSA SAF).

- Regional FFTs classification, SE-S Bulgaria (Stoyanova, 2007).
- 0600 UTC MSG LSA SAF: ET, LST, FVC MSG 5x5 pixels inferred numerical values and centered at the locations of synoptic stations network (for cloudless slots) for the regions of FFTs only and GLCM2000 in MSG projection.

(a) (b)

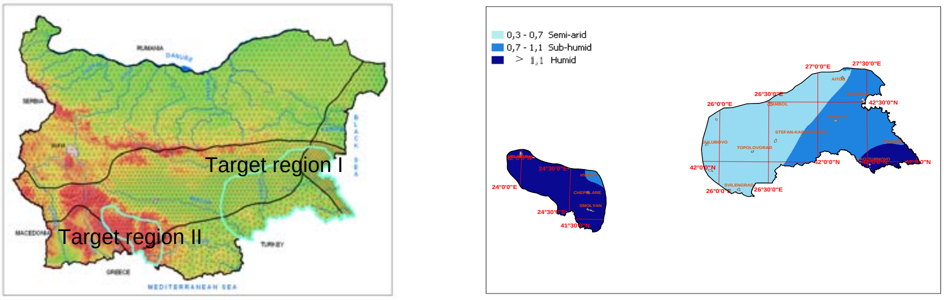

Fig. 3. Plot of selected target region for the study: (a) Physicogeographycal location of Target region I and II; (b) Climatic atmosphere aridity classification (Rainfall vs. PET (Ivanov)).

In evaluation the concept used reference information includes: Dataset of actual forest fires registered by the State Forest Agency of Bulgaria; Vegetation distribution from field observations and experience in Bulgaria.

RESULTS:

Regional FFTs structural and functional properties:

As a first step, the correspondence between regional model estimates of FFTs and global vegetation maps used in MSG projection is considered. The classified FFTs regions over Bulgaria (Fig.2) are related to corresponding areas of vegetation types from GLC2000 land cover classification map (Bartholome and Belward, 2005), which breaks down the land cover categories into 22 biomes (Vegetation Types, VT). The relation includes the following correspondences:

- **FFT1** (tree cover, broadleaved xeromesophytes) corresponds to ***VT 2*** *'Tree Cover, broadleaved, deciduous, closed'*
- **FFT2** (open deciduous, shrubs) corresponds to ***VT 12*** *'Shrub Cover, closed-open, deciduous'*
- **FFT3** (native coniferous, evergreen) corresponds to ***VT 4*** *'Tree Cover, needle-leaved, evergreen'.*

As a second step, MSG based information is used to characterize differences in functioning of FFTs during vegetation and their corresponding structural features for selected sites within each one unit (Fig. 4). Flux of water evaporated at the earth-atmosphere interface from different FFTs that is a key link between the energy and water cycles is evaluated by the LSA SAF ET product dynamics (Fig. 4a). The dependences derived show:

a) b) c)

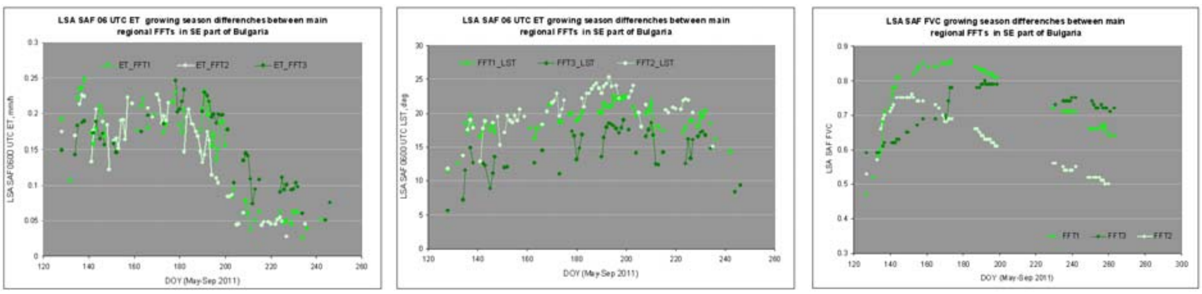

Fig. 4. Dynamics (May-September 2011) of functional and structural properties of regional FFTs (according Fig. 2: for FFT1 at 41.96N 27.58E, FFT2 at 41.505N 25.78E, FFT3 at 41.7N 24.7E), as seen by MSG SEVIRI: (a) 06 UTC LSA SAF ET product; (b) 06 UTC LSA SAF LST product; (c) LSA SAF FVC product.

- FFTs differ each other regarding the ET growing season dynamics. At the beginning of vegetation, FFT1 exhibits the highest ET, followed by FFT2, while coniferous FFT3 have the lowest ET.
- At the end of growing season (September 2011) FFT3 is more actively functioning than the broadleaved deciduous FFT1 and FFT3.

The second functional characteristics under consideration, involved in the processes of energy and water exchange with the atmosphere is the radiative skin temperature over land, LST (Fig. 4b). Its space variability is modulated by surface properties like vegetation density (Fig. 4c) and soil moisture.
Looking at the structural FFTs properties according to the FVC dynamics (Fig. 4c), in May as it could be expected FFT1 shows highest FVC, followed by lower values for FFT2 (open deciduous, shrubs), and the lowest FVC for the FFT3 (coniferous, evergreen). At the end of vegetation (September 2011) the FVC differences among the three FFTs are opposite and in accordance to their functioning. In the considered regional assessment by satellite data, the LSA SAF products successfully reflect the differences in FFTs characteristics. The results are in conformity with the main biogeophysicals/ ecophysiological principals of functioning of coniferous (FFT1), closed and xeromesopyte deciduous forest (FFT1) and the dry habitats of low productive oak forests and shrubs in the LFB (FFT2).

Biomass burning pattern related to regional FFTs:

Characterization of climate-forest-fire pattern using MSG measurements of biomass burning fire radiative energy is presented on Fig. 5 and Table 1 for three years with different fire activities: ‘high’ (2012), ‘medium (2011) and ‘low’ (2010) according to the Bulgarian SFA database.

a) b) c)

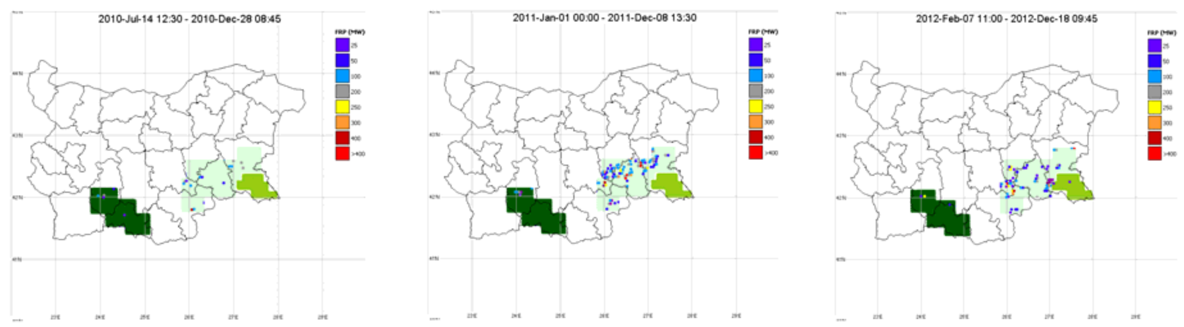

Fig. 5. Accumulated fire radiative energy released by fires in the areas of FFTs over South and South-eastern Bulgaria (FFT1 in medium green, FF2 in light green, FFT3 in dark green) derived by satellite LSA SAF FRP product for: (a) 2010, (b) 2011 and (c) 2012.

Table 1. Accumulated fire radiative power and carbon equivalent released by fires in the areas of FFTs over **South and South-eastern** Bulgaria, derived by satellite LSA SAF FRP.

Year Regional FFTs		**2010**	**2011**	**2012**
FFT 1	Total FRP (MWatt)	0	0	55.0
	Carbon Eq. (kg)	0	0	8507
	Pixel number	0	0	2
FFT 2	Total FRP (MWatt)	1209.4	13697.3	37616.8
	Carbon Eq. (kg)	187059	2118572	5818202
	Pixel number	18	186	275
FFT 3	Total FRP (MWatt)	275.0	2111.3	641.0
	Carbon Eq. (kg)	42534	326555	99158
	Pixel number	7	30	9
Number of forest fires (SFA data)		**222**	**635**	**878**

Following the regional PFTs classification scheme, vulnerability of FFTs to fire hazard is characterized using capabilities of LSA SAF FRP product. Accumulating all pixel detections and biomass burning effects (total fire radiative energy and fire-carbon equivalent emitted), the following pattern is revealed:

- Most frequently fire pixels are detected in the **FFT2** area. This trend is valid for years with 'high' (2012), 'medium (2011) and 'low' (2010) fire activities, (after the SFA of Bulgaria reports).
- **FFT2,** composed predominantly by native dry stand oak stands and shrubs, are the most fire prone area and are providing the highest climatic forcing of FRE = 52523.5 MWtt for all 3 years.
- **FFT1,** composed predominantly by xero-mesophytes native deciduous oak stands, are the less fire prone area, providing the lowest climatic forcing of FRE = 55.0 MWtt for all 3 years.
- **FFT3,** composed predominantly by native coniferous stands are moderate in fire activity and climatic forcing – FRE = 3027.3 MWtt for all 3 years.

CONCLUDING REMARKS

In the present work a methodological approach to contribute the estimation of regional static fire risk for a selected region in the Eastern Mediterranean is introduced. A scientific scheme for validation of LSA SAF products (FRP, ET, LST, FVC) (in conformity with EUMETSAT recommendations, Schmetz, 2013) is also proposed.

Three data sources are used to derive the fire potential: forest fuel types corresponding to regional biome classification, SEVIRI satellite sensor quantitative geophysical indexes to discriminate differences in the structure/functioning of vegetation types, and ground observations. Accounting that potential forest (biomass) distribution is a result of climatic differences, a static Bulgarian model for the main regional vegetation cover types (forest-PFTs differentiation, FFTs) is applied as a starting point for the comparative analyses. Vulnerability of FFTs to fire hazard is characterised using capabilities of LSA SAF FRP product. The ranking reveals that the most fire prone is FFT2 area (the dry habitats of low productive oak forests and shrubs in the Lower Forest Belt), followed by native coniferous FFT3 and the less fire prone is the area of FFT2 (closed and xeromesopyte deciduous forest) (Fig. 2 and Fig. 3a). Accounting for satellite measurement of FRE release rate or power enables distinction between fires of different strengths.

The first results show that MSG FRE estimations for the region of SE-S part of Bulgaria can reveal climatic controls on fire frequency and forest pattern influences aspects of fire regime. Based on especially designed methodological approach for characterizing climate-forest pattern relations, results provide a first step in ranking of natural forest cover regarding susceptibility to fire ignition and spread, and give knowledge towards understanding of vulnerability of land systems to fire on a regional scale, in support to forest management and policy.

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