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Article

Probabilistic Wildfire Risk Assessment and Modernization Transitions: The Case of Greece

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Abstract: Wildfire is the primary cause of deforestation in fire-prone environments, disrupting the forest transition process generated by multiple social-ecological drivers of modernization. Given the positive feedback between climate change and wildfire-driven deforestation, it seems necessary to abstract the primary- or micro-characteristics of wildfire event(s) and focus on the general behavior of the phenomenon across time and space. This paper intends to couple wildfire self-organizing criticality theory (SOC) and modernization statistics to propose a verisimilar explanation of the phenomenon's evolution in the past decades and a prediction of its trends in Greece. We use power law distributions of the fire frequency–magnitude relationship to estimate the basic SOC parameters and the Weibull reliability method to calculate large-size wildfires' conditional probability as a time function. We use automatic linear modeling to search for the most accurate relationship between wildfire metrics and the best subset of modernization predictors. The discussion concentrates on reframing the political debate on fire prevention vs. suppression, its flaws and limitations, and the core challenges for adopting more efficient wildfire management policies in Greece.

Keywords: self-organizing criticality; interoccurrence interval time; political competition

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1. Introduction

It is commonplace that many environmentalists, conservationists, or spatial planners, originating from the natural or social sciences, profess that an enormous scope of human activity exerts significant pressures on the biosphere. The broad spectrum of human activities increasingly overshoots global biocapacity, rapidly erodes biodiversity, degrades ecosystem functions and services, and downsizes the natural capital flow, measured in monetary units [1–4]. The pragmatic acceptance that the human impact on Earth is so pervasive that nature as independent from and unimpacted by humans no longer exists [5,6] and reshapes scientific worldview(s) and research priorities, even on long-established themes and approaches of natural phenomena, such as wildfire [7]. Integrating fire as (1) an energy dissipation event in mean-field geo-physics [8]; (2) a physiochemical process between oxygen, heat, and fuel [9]; (3) an evolutionary factor for species in fire-prone environments [10]; and (4) a monopoly of *Homo sapiens* [11] that interferes with the fire regime [12] and significantly influences fire risks and hazards [13], necessitates a scientific paradigm [11] and an organizing principle to consider fire, its environmental effects, and its management challenges. The pyric transition concept and the pyric phases model [14,15] currently represent the incumbent theoretical framework of the wildfire phenomenon on Earth. One should consider the authors' ascertainment that pyric transitions have had different paces in different parts of the world, and all pyric stages coexist in modern times.

Earth-system scientists reasonably concur in condensing the findings of the abundant multi-disciplinary wildfire literature through some core predictions: (1) wildland fire is a major cause of global deforestation, along with commercial and subsistence logging and the conversion of forests to agricultural land and pasture [16–18]; (2) there is a potential positive feedback between climate change and landscape burning, although estimates of fires' contribution to the increase of radiation forced into the atmosphere, changes in surface reflectivity, total emissions of $CO_{2,}$ and release of black carbon aerosols show spatiotemporal variations [19,20]; (3) although climate change *per se* rarely causes fire ignition, it plays a catalytic role in fire events' severity [21], even of a disastrous character [22], and likely is increasing fire incidences and amplifies damages and risks to humans and infrastructures [23].

Remarkable progress is achieved regarding fire research's physical and biological fundamentals, especially the modeling pillar, which derives most explanations and predictions from fire as a systemic phenomenon [24]. The gradual emergence of the cultural paradigm in wildfire science indicates the conceptual striving for fire to be considered as an organizing device for human occupation of the planet [11]. As a concept and a historic move, the pyric transition might be the center of such an endeavor. Any transition should be viewed as an evolving, vaguely defined, social-ecological condition where multiple stressors cooccur and are confounded and connected. Forest transition, or the balance or turnaround between deforestation and regrowth [25], is intricately and functionally related to (1) the demographic transition [26], (2) the cultural and political Westernization transition [27], and (3) the modernization transition [28]. In a succinct description, economic growth, urbanization, and industrialization processes first led to a deforestation phase. Then, rural depopulation, land abandonment, and the concentration of agricultural activities on fertile soils create the conditions that allow forests to recover. These trajectories are predicted or described by the Ecological Modernization Theory in sociology [29] and the Environmental Kuznets Curve (EKC) theory in economics [30], assembling both advocative and critical narratives around them. More and more, the literature digging deeper into these general syndemic patterns of human pyric activities and social evolution in modern times points its finger at bad environmental governance moderators of the above primary relationships. For instance, the ambiguous legislative role of politicians or administration officers, corruption, the inadequate justice system, organized crime, and so on are pointed out in the literature [31–34].

As pyrogeography [15] is required for solving practical wildfire management problems, its scientific practice is a bottom-up search of statistical regularities; insofar as it aspires to underwrite talk about fundamental mechanisms and identification of wildfire causes or drivers, top-down approaches are needed [35]. In this epistemic bifurcation, the bottom-up-oriented literature accumulates examples of the interactions or relationships between wildfire ignition, occurrence, risks, hazards, landscape-level transitions, and modernization processes. For instance, the probability of wildfire occurrence as a function of land abandonment [36], forest transition through natural afforestation or planting [37], expansion of urban areas, and the wild/urban interface [38], population density [39], or development of the road system [40]. In most cases, such independent variables are treated separately, e.g., fire occurrence probability vs. population density [39].

From the top-down modeling perspective, the exciting part of the above theoretical refinement is the development of sophisticated modeling techniques necessary to abstract primary- or micro-characteristics of wildfire event(s) and focus on general behaviors. One could identify three fields where advances are remarkable. The first relates to self-organizing complexity (SOC) theory and statistics [41–47]. In SOC systems, such as the ecosystem where wildfire occurs [48], energy dissipation events' frequency–magnitude distribution follows a power–law relation [44]. The second field relates to the power–law distribution of time intervals or interoccurrence time between wildfire events of a certain magnitude [49–51]. The theoretical and empirical investigation of power laws in complex systems, from linguistics to networks and fractals, and their applications in natural and social phenomena offer a solid background on examining scale-invariance and time-invariance dependence of wildfire occurrence frequency on the burned area over orders of magnitude. The third field refers to statistical models that address functional relationships between predictor variables and the response used and tested in the broad case of deforestation. From simple OLS regressions [52] to least-absolute-deviation quantile regression [53] and most sophisticated generalized additive models [54], to hierarchical generalized linear models and hierarchical generalized additive models [32,55], significant steps are made in extending the standard linear regression framework. These advances allow for identifying smooth functional relationships between predictors and responses varying between groups and testing whether such relationships hold across the compared groups. We refer to predictor variables approximating different biophysical, demographic, economic, or even governance factors and indicators, and to some response variables, i.e., a measure of pyric activity or effects, e.g., number of fires or burned areas per vegetation type.

One might take the chance to depict this rationale using, somehow abusively, the triangular pyrogeographic scheme [14,15]. Figure 1 is a graphical representation of this paper's goals and contributions. We aim to explore the feasibility and potential of coupling long-term wildfire occurrence statistics as a SOC phenomenon by empirically estimating its hazard or interoccurrence time, i.e., the interval between fires on all vegetation setups nationwide under modernization-driven social-ecological conditions. The questions we attempt to shed light on are (1) the functional relationship between the response variable, i.e., a metric of wildfire, and potentially important explanatory variables, i.e., the modernization stressors; (2) the estimation of parameters of the wildfire occurrence frequency–magnitude (per vegetation type at an annual scale), especially the scaling exponent of a power–law; (3) the parameters of the hazard function of wildfire interoccurrence time, nationwide. This triptych is essential for devising strong, integrative, long-term wildfire management policies.

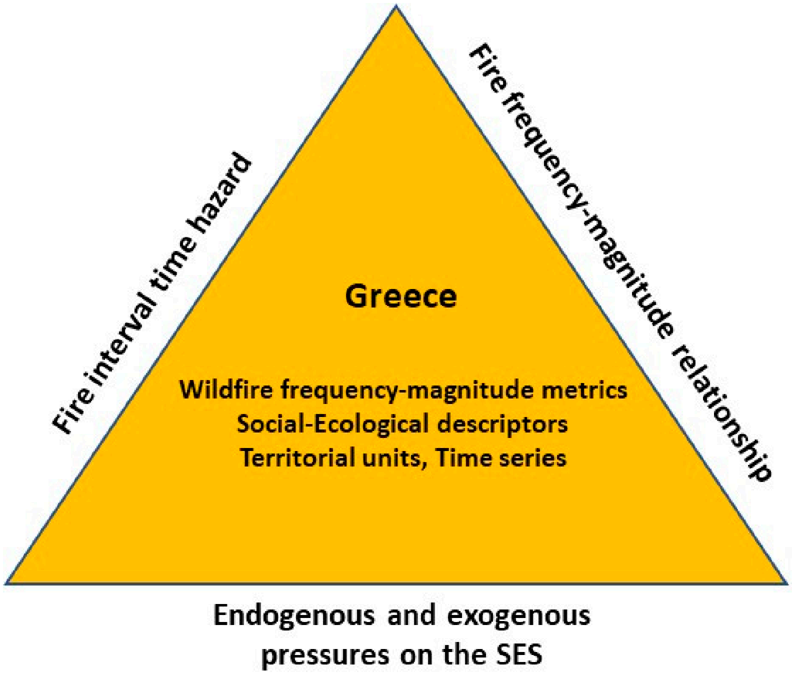


Figure 1. A triangular representation of the relationships between three determinants of wildfire occurrence under modernization transitions. The basal side of the triangle refers to the functional relationship between some metrics of wildfires and a series of endogenous and exogenous modernization and other administrative and political predictor variables of the social-ecological system (SES). The right side of the triangle refers to the basic form of the SOC statistics component. The left side of the triangle refers to the statistics of recurrence or interval times between wildfire events. Reference is made to Greece as it is our model case for the period of 2000–2021. Details of the mathematical formulations are given in the Methods section.

2. Materials and Methods

The case study is in Greece, a Mediterranean Basin country, where wildfires are abundant in numbers and are recurring. We used the Hellenic Fire Fighting Corps wildfire database, covering 2000–2021, at various spatial scales, fire ignition times, and landscape setups. We aimed to examine whether wildfire frequency–size distributions provide information on calculating risk and, eventually, hazard mitigation.

2.1. Preliminary Remarks

This section consists of three parts. For convenience reasons, we prefix the following remarks. First, we use the term 'wildfire' to characterize fire events in 'wooded lands', i.e., a mosaic vegetation landscape consisting of forest clusters, afforested lands after the abandonment of cultivations or plantations, mixed shrub- and grass-dominated patches (i.e., maquis, garrigues, or phrygana), and very often, olive-groves. Many fires are ignited in one vegetation type and spread over larger areas housing multiple vegetation types. This choice was deemed necessary because of the spatial complexity of a typical Mediterranean Type (MT) vegetation mosaic.

Second, the term 'forest fire' is used only in cases of officially designated forest areas that are burned. A reader should remember that Greece has had no definitive cadastral plans and forest maps since the end of 2022. Then, the official classification of woodlands as a forest resulted from aerial photographic coverage of the territory taken in the WWII years. Despite the difficulties in strictly classifying burned vegetation, e.g., the 'official forest' vs. the afforested lands, this institutional defect influences, rather substantially than negligibly, arson [56].

Third, we call a stressor any driving force, be it natural, social, or economic, that induces changes in human–nature interactions that affect the probability of wildfire. Fourth, to differentiate between single vs. combinations of stressors, we adopted the term 'ultimate' for the former and 'proximate' for the latter, indicating that there are interconnections or co-foundations between them.

We also present the preliminary diagrammatic transformation (Figure 2) of the above triangular scheme and the mathematical formulations of the relations between the components. Central to our approach is a heuristic element we call a 'wildfire metric', $\varphi_{t(i)}$. We define $\varphi_{t(i)}$ as the ratio of a measure of wildfire activity (e.g., number of events, size of the burned area: nationwide or per administrative jurisdiction or vegetation type) in year $t = 1 \ldots i$ over the same measure in the base year $t(0) = 2000$. Assuming that some power–law function fits the fire occurrence frequency–magnitude distribution, one writes this ratio as:

$$\varphi_{t(i)} = \frac{f(s)_{t(i)}}{f(s)_{t(0)}} = \frac{Cs^{-\gamma_{t(i)}}}{Cs^{-\gamma_{t(0)}}} = s^{\left(\gamma_{t(0)} - \gamma_{t(i)}\right)} = s^{\xi_\iota} s \in \mathbb{R}, \gamma \in > 0 \tag{1}$$

where $f(s)$ is the generic form of the power law distribution (PLD), C is a constant, and γ is the exponent or scaling factor of the PLD.

Further, in Figure 2, M describes a set of modernization stressors, and f(M) is a function (linear vs. non-linear, i.e., hyperbolic or parabolic) of social, economic, political, or ecological explanatory variables; $F(s)$ is the complementary cumulative density wildfire frequency–magnitude power–law function (PLD); $h(t_0)$ is a hazard function as a function of time of a characteristic event, $h(t)$, calculated after a 2-parameter Weibull distribution, i.e., shape τ and scale γ.

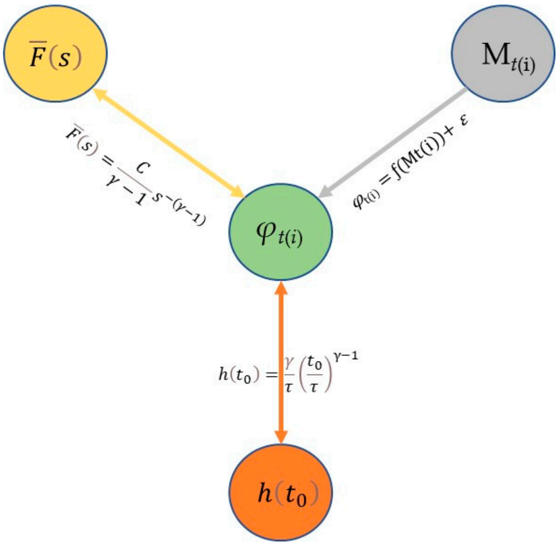


Figure 2. A diagrammatic transformation of the triangular representation of the determinants of wildfire occurrence under modernization transitions. The definitions of the poles and the corresponding mathematical formulations are explained in detail in the text.

2.2. Descriptors and Data

Table 1 shows the metadata on the data series and summarizes the statistical procedures adopted, given the nature and variability of the social-ecological stressors studied. Details on measurement units, types, and sources of data are presented in Table A1.

Table 1. Synopsis of metadata and methodology of the study of the relationships between the three determinants (modernization, fire frequency–magnitude relationship, interval times) of wildfire occurrences under modernization transitions in Greece, 2000–2021.

Methodology	Metadata	Remarks
Case study	Country: Greece	Although wildfire data are recorded at the Department level (51), country-wide sums are used here.
Range	2000–2021	More extensive periods were used when data were available, e.g., 1990–2021 or 1955–2021.
Relationships		
Power-law distribution	PDF, CDF, cCDF	Probability Density Function, Cumulative Density Function, Complementary Cumulative Density Function
Models	Linear, Hyperbolic, Parabolic	Detection of the best-fit model
Dependent variables	Burned area, number of wildfires, interval times/year	Calculations of scaling factor γ, the lower size of burned area s_{min}, upper size s_{max}
Independent variables		
Modernization variable	Penetration RES (%), (GDP_PPP $)	RES: Renewable Energy Sources, PPP: Purchasing Power Parity
Complementary variables	Population change, wooded areas%, agricultural land%, rural population density, automobile fleet, energy consumption/cap, political risk, climate anomalies	Collinear variables excluded
Regressions	Automatic Linear Modeling procedure	Definition of one subset from the pool of candidate predictors that gives adequate prediction accuracy as an alternative to various regression methods

2.3. Modernization Stressors Trends

Modernization is not a measurable condition per se; it is a slowly evolving social, economic, and environmental transition process. In that sense, one can only associate modernization with adequately measurable stressors. Those we consider as plausible proxies expressing macro-aspects of material structural modernization of the Greek society that might interfere with forest transition processes [25,32,37,52,53] are presented in Table 2.

Table 2. Synopsis of independent variables (stressors) used in calculating wildfire metrics' (response) relationship with material macro-structural aspects of modernization. Meteorological and political events are also listed as potential moderators of these variables.

Modernization Stressors	**Remarks/Definitions**
Population size Urban population density Rural population density	Total number of individuals residing during a census period Population density is midyear rural or urban population divided by the corresponding land area in square kilometers.
Agricultural land % Wooded land %	Agricultural land is the share of arable land under permanent crops and pastures. A forest (wooded) area is land under natural or planted trees of at least 5 m in situ.
GDP/cap_PPP $US	Per capita values for the gross domestic product in current international $ converted by purchasing power parity (PPP) conversion factor.
Energy consumption/cap	Production of power plants and combined heat and power plants less transmission, distribution, and transformation losses and use by heat and power plants.
RES/Hydro in energy mixture	% of the energy produced by Renewable Energy Sources and Hydropower plants
Automobile fleet	Total of cars, trucks, motorbikes
Political competition	General elections for the Parliament
Climate anomalies	Annual deviations (positive or negative) of mean temperature and precipitations from the 30-year average trend

Most literature on the impact of variables approximating modernization arranges environmental response metrics across countries or regional setups in a specific time corresponding to different proxies' levels, e.g., economic growth, urbanization, or industrialization. This intercountry arrangement plays the role of time. Typically, per capita income is the first variable included in the simplest models [57]. In such cases, the trajectory of a dependent environmental variable, e.g., biodiversity [58], deforestation [53], or gaseous emissions [59], assimilates the time evolution of the phenomenon. This is not the case in this contribution since we address the dynamics of wildfire metrics in *one country* over *several years*. Data series per independent variable integrate many multi-leveled and interconnected drivers, exogenous and endogenous, to Greece's Social-Ecological System (SES). Real-world interannual fluctuations of stressors are expected for any country, blurring thus theoretical models; Greece recorded several of repeated and violent volatility (i.e., the world economic recession 2008–2009, the National Sovereign Debt default, austerity crisis 2010–2018, COVID-19-related recession 2020–2021, and world energy crisis 2021–2022). In the context of Greece, we assume that the GDP growth, a modernization stressor typically used in ecological modernization literature [29,30], is inconsistent because of multiple, sequentially interfering, financial pressures on the country's economy during the studied period. Although GDP/cap is included in the set of modernization indicators and is tested similarly to the rest, we intuitively select the penetration of Renewable Energy Resources (RES) and Hydroelectricity plants in the energy mix of Greece as an appropriate modernization indicator. RES development conceptually overlaps with economic growth and encapsulates social conflicts over land allocation, investment, and infrastructure construction.

The literature on the environmental effects of modernization focuses on differentiating between three generic models, i.e., the inverse U-shaped parabolic relationship predicted by liberal theories in sociology and economics [29,30] vs. critical political economy theories accepting either decreasing linear or hyperbolic relationships [60,61] (Figure 3). Various regression models have been proposed [52–55,62–64]. Here, we apply the Automatic Linear Modeling (or regression, ALM) functionality provided by the IBM SPSS v28 procedure [65]. In this case, the goal is to evaluate multiple promising subsets of stressors that are best according to the optimality criterion of choice, Akaike's Information Criterion corrected. To estimate, besides the linear, potential non-linear relationships between predictor variables and response, quadratic terms, or inverse transformations of the predictor variables are included in the set of variables.

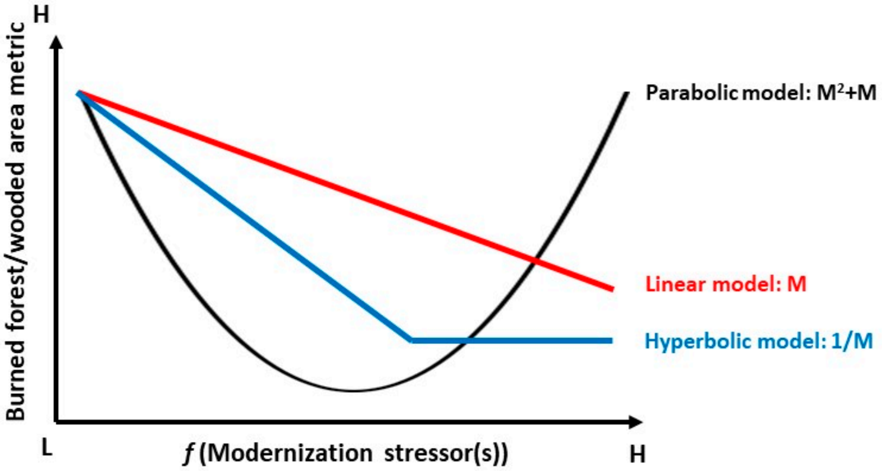


Figure 3. Three hypothetical forms of the relationship between the best subset of modernization stressors and a metric of pyric activity, e.g., burned areas in Greece, 2000–2021.

2.4. Estimation of Parameters of Wildfire Frequency–Size Distributions Methodology

The literature accepts that most geophysical phenomena related to energy dissipation show power–law behaviors predicted by the general theory of self-organized criticality (SOC) [43]. Forest-fire occurrence frequency vs. size PLD relationship is extensively studied (>250 publications in the Web of Science as of the end of 2022) and empirically confirmed in various ecological setups. Usually, the occurrence frequency of fire, or fire frequency, for different sizes of fire is calculated as [30]:

$$F(s) = -\frac{d\dot{N}_{(s'>s)}}{ds} \tag{2}$$

where $\dot{N}_{(s'>s)}$ is the annual number of fires with a burned area greater than s. This corresponds to the cCDF (or its log-log transformation) of the PLD, i.e.,

$$F(s) = \Pr(s_i > s) = 1 - F(s) = \frac{C}{\gamma - 1} s^{-(\gamma-1)} \tag{3a}$$

$$\log F(s) = \log\frac{C}{\gamma - 1} - (\gamma - 1)\log s \tag{3b}$$

$F(s)$ being the CDF of the PLD or $F(s) = \Pr(s_i \le s)$.

The random variable for each yearly wildfire dataset (corresponding to each vegetation type) is the absolute frequency n of each fire size class. The number of appearances of each frequency value, i.e., the frequencies of frequencies, constitutes an empirical estimation $f(n)$

of the probability mass function of the frequency. Although n is a discrete count, we treat them as a continuous random variable and estimate its empirical probability density using logarithmic binning (primarily for visualization). So, $f(n)$ denotes, in fact, a probability density and its empirical estimation [66].

All distributions present many values that only occur once (n = 1) (for example, the maximum size of burned area s_{max}), as well as values with very high frequencies ($n > 10^4$, or $s_{min} \to 0$ but always >0 in the global dataset), with a decaying curve linking both extremes. Overall, we focus on estimating the interannual variation of quantities of interest, i.e., the scaling factor γ, the lower limit (smaller size) of burned area $s_{min,}$ and the upper limit s_{max} (which is de facto truncated) of the fire frequency–size distribution. Our procedure follows classic demonstrations [67–70], i.e.,

$$\hat{\gamma} = 1 + n\left[\sum_{i=1}^{n} \ln \frac{s_i}{s_{min}}\right]^{-1} \tag{4}$$

$$\hat{s}_{max} = \left[n\frac{1-\hat{\gamma}}{\hat{C}} + s_1^{1-\hat{\gamma}}\right]^{\frac{1}{1-\hat{\gamma}}} \tag{5}$$

where $\hat{\gamma}$, $\hat{s}_{max}$, and $\hat{C}$ are estimates of the scaling factor, the upper-limit size, and the normalization constant. s_1, the smallest observation, is used as an estimate for $\mathrm{s_{min}}$. Notice that $\mathrm{s_{min}}$, the lower limit or threshold of the PLD, is the value that minimizes D, the maximum distance between the data and the fitted model of $F(s) = \Pr(s_i \leq s)$, using a Kolmogorov–Smirnov test approach to calculate it [69]. The calculations are made in R using an adapted version of the power–law package [71].

2.5. Estimation of Parameters of Wildfire Interval Times Distributions Methodology

An essential property of SOC models and geophysical phenomena is the statistical distribution of the interval times of recurrent events [51]. These large events are often called characteristic events, characterizing peak values of the sequence of events [49]. Interoccurrence times are the time intervals between wildfires nationwide. Defining the magnitude of a characteristic event is a matter of scale; for instance, in constructing the Equivalent Hazard Magnitude Scale [72] for forest fires, only burned areas ≤200,000 km^2 were included. Given that the national territory is 132,000 km^2, we consider wildfires >10 km^2 a peak event compared with threshold events, which are usually 1 km^2 in Greece.

Here, we address interval times distribution, i.e., the distribution of time elapsed between wildfire events, for both characteristic and threshold events. These calculations are applied to two vegetation types, i.e., forest and wooded areas. Hazard function as a function of time of a characteristic event, $h(t)$, is calculated after a 2-parameter Weibull distribution, i.e., shape τ and scale γ. The CDF for the Weibull distribution is given by

$$P(t) = 1 - \exp\left[-\left(\frac{t}{\tau}\right)^{\gamma}\right] \tag{6}$$

and the hazard function, which presents power–law behavior, is

$$h(t_0) = \frac{PDF}{1 - CDF} = \frac{\gamma}{\tau}\left(\frac{t_0}{\tau}\right)^{\gamma - 1} \tag{7}$$

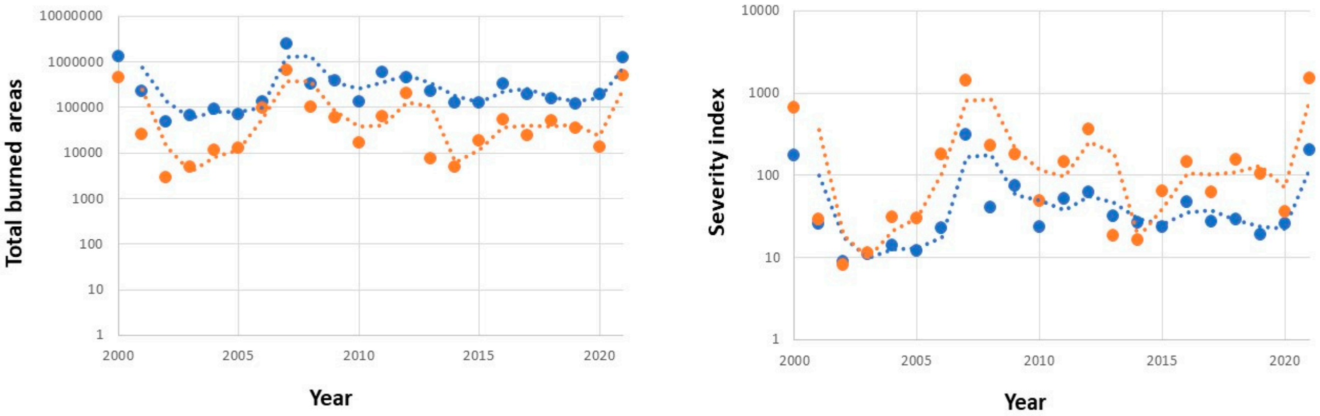
The hazard function must increase for characteristic fires as the time since the last characteristic fire t_0 increases. The Weibull distribution with $\gamma > 1$ is the only distribution showing an increasing hazard function with increasing t_0. It is standard practice to test the validity of a Weibull distribution using a Weibull probability plot constructed after plotting interval times data in a 2D plan.

$$\log[-\ln(1-P(t))]\text{vs.}\log\left[\frac{t}{\gamma}\right] \tag{8}$$

The Weibull distribution requires a straight-line fit with slope γ. The corresponding fitting parameters for shape and scale are calculated after the regression or maximum likelihood estimation methods in the Solver Excel Add-In using the observed interval times.

3. Results

Results are presented in the following order: the findings on the wildfire frequency–size distributions, followed by those on fire interoccurrence time intervals; results on the relationship(s) between modernization stressors and wildfire frequency metrics end this section. Indicative but exemplary results per subsection are presented to accompany the narration. Greece recorded 148,000 fire events and 9000 km^2 of burned areas (forests, afforested areas, shrublands, and agricultural tree plantations) during 2000–2021. Fire events in 'officially designated forests' are 9400 and burned surfaces are 2500 km^2. The severity index, i.e., the ratio between surface burned and the number of fire events per year, shows variations of two, even three, orders of magnitude (Figure 4). However, the long-term severity index, i.e., 1955–2021 or the period during which fire statistics data exists, shows a positive but non-significant slope (standardized B = 0.131; p = 0.281). The interesting remark after these general results is that the severity index of forest fires is almost systematically higher than landscape or wooded areas fires.



(**a**) (**b**)

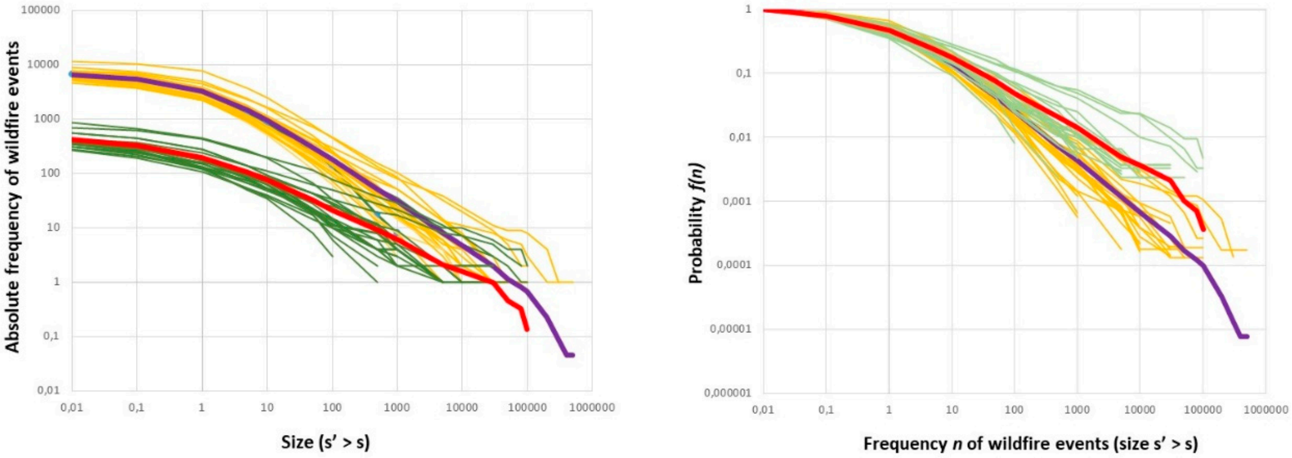
Figure 4. Evolution of wildfire statistics in Greece, 2000–2021; blue dots: all vegetation types summed, orange dots: forests. (**a**) Total burned areas; (**b**) Severity index (ratio surface burned/number of events). Dotted lines: moving average, lag period = 2.

3.1. Wildfire Frequency–Size Distributions

The results of the wildfire frequency–size distributions (at an annual scale, nationwide, per vegetation type, a total of 22 distributions) may be summarized in three points:

- In eighteen over twenty-two years, burned areas are distributed as a single power–law, represented by a straight line in log-log scale; in the remaining four, a double power–law fits the actual distributions better;
- since 2000, the frequency of small-sized forest fires has increased;
- the evolution of the γ-scaling factor for forest areas presents a significant negative slope (standardized B = -0.297; p = 0.047), whereas it is non-significant for wooded areas (standardized B = 0.48; p = 0.861).

These empirical results agree with the theoretical studies on self-organized critical forest-fire models. This supports the idea that knowledge of the occurrence frequency of small and medium fires can be used to quantify the risk of large fires. Figure 5 presents the absolute frequency cumulative distributions of burned areas (forests and all vegetation types) and the corresponding empirical probability densities of the frequency *n* of wildfire events. The coefficient of variation of s_{max} for forests is 2.75, whereas for all vegetation types it is 1.63. It suggests that as the number of initial events in forests increases, the probability of large-sized forest fires increases too.



(**a**) (**b**)

Figure 5. (**a**) Absolute frequency cumulative distributions of burned areas of size s′ > s. (**b**) Empirical probability densities of frequency *n* of wildfire events (size s′ > s). In both panels, annual distributions are color-coded: green lines: forests; orange lines: wooded areas (including forests). Bold red and purple lines are the respective average distribution, as a simile aggregation, derived from the corresponding vegetation type global dataset.

Figure 6 presents indicative results on the scaling factor γ of the PL fire frequency–size relationship. In 2005, considered a low fire severity year, the γ-scaling factors for wooded and forest areas are very similar. When the relationship is modeled as a broken PLD, i.e., as a piecewise function consisting of two power–laws combined with a threshold value, this threshold corresponds to the same value of the burned area, i.e., $\leq$10 ha. Further, Figure 6 presents the fire frequency–size relationship in 2007 and 2021, showing almost identical γ-scaling factors. These examples are educative on public perceptions of the phenomenon since they are considered the most catastrophic in terms of burned areas (>100,000 ha), currently referred to as mega-fires; further, the 2007 mega-fire was also disastrous in terms of human casualties (=84 deaths), infrastructure (>1500 houses), agriculture (>4,500,000 olive trees), and husbandry (>60,000 animals) [73]. On the contrary, although >210,000 ha burned in 2021, there were no human casualties. In 2018, the Attica wildfires were socially traumatic [74] since they caused the second-deadliest record worldwide during the 21st century—killing 102 people—but their medium size per se was 1250 ha in a sea-shore, residential, wild-urban interface area.

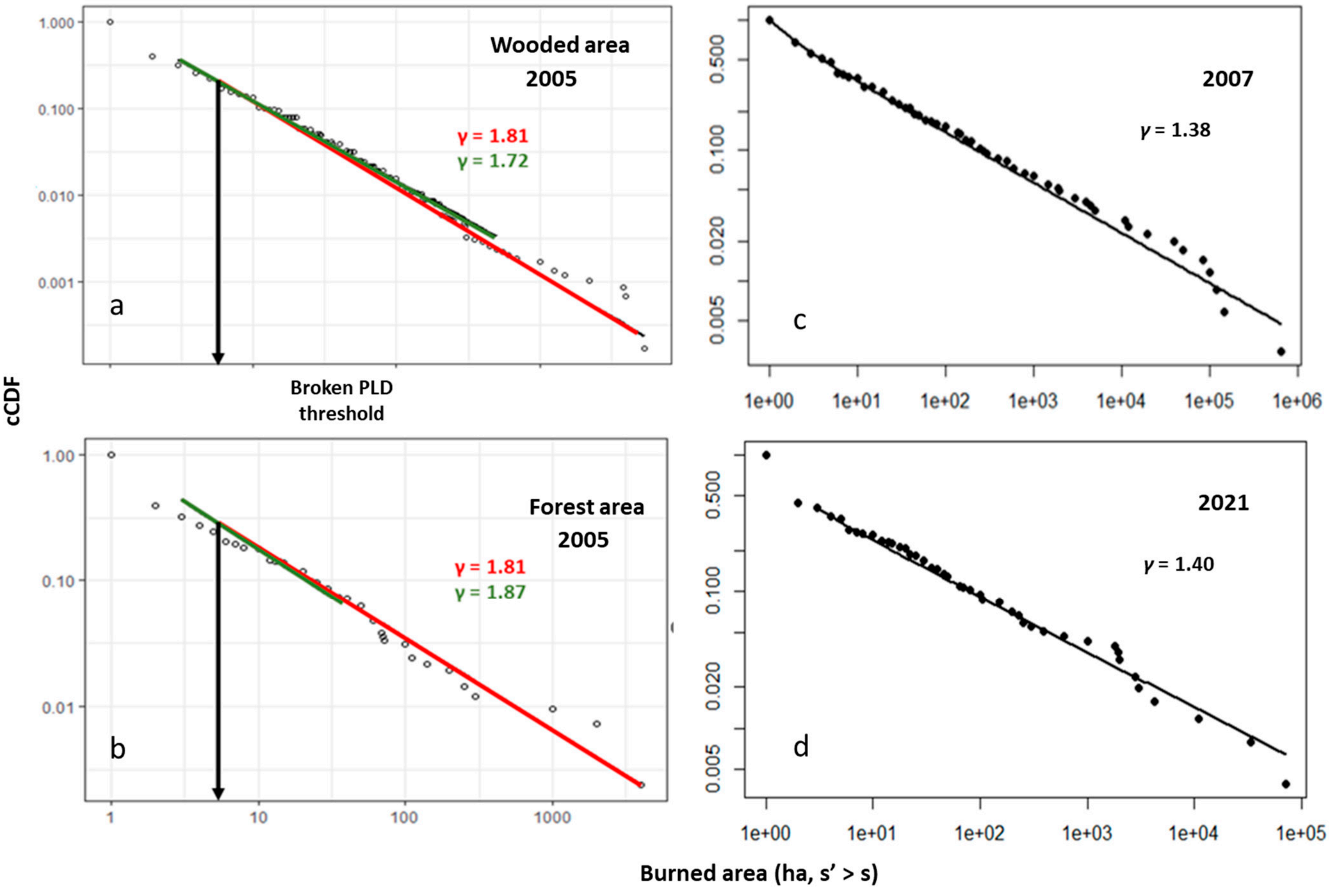


Figure 6. Indicative examples of the wildfire frequency–size power–law relationship and the corresponding value of the γ scaling factor. (**a**) Log-log PLD relationships in wooded areas and (**b**) forest areas in 2005, a year of low wildfire severity index value. The overall relationship is modeled as a broken PLD (two power–laws combined). The linear log-log relationships are very close for wooded and forest areas burned. The threshold value is identical. (**c**,**d**) Log-log PLD relationships between wildfire frequency–size in forest areas during 2007 and 2021, the highest wildfire severity index value in the 21st century. Notice the range of sizes (x-axis) and the similarity of the respective γ-scaling factors.

3.2. Wildfire Time Intervals Distributions

A question relevant to fire management is the calculation of the conditional probability of major wildfire events in some time horizon. Figure 7 shows three examples of wildfire time interval distributions, considering alternative sizes of the characteristic forest fire events and periods. Figure 7A focuses on the interoccurrence time of all events, >0.1 ha yearly. For instance, in 2000, 626 forest fire events were recorded, and the total forest area burned was 45,522 ha. The Weibull distribution perfectly fits the phenomenon (Weibull probability plot $R^2 = 1$), leading to a probability distribution with a scale parameter of 235 (ha). In cases of characteristic events of medium (>1000 ha) and large (>5000 ha) size (Figure 7B,C), the number of events recorded during the entire period of observation is much fewer; the probability distribution scale parameter is 2870 and 4600, (ha) respectively. However, the medium size wildfires burned more forest areas (168,671 ha) during the observation period of 2000–2021, the large ones having burned almost half (94,343 ha). Figure 8 presents the conditional probability of a major wildfire event, i.e., $s \geq 5000$ ha, in Greece in the next five years, calculated as 1—Weibull reliability function. The probability of such an event is quite remarkable (ca 40%). The message for Civil Protection authorities is that no matter how efficient it might be considered, at an annual scale, with the business-as-usual wildfire suppression plan on the ground, there is a need to reconsider and address the significant social and ecological drivers of the wildfire phenomenon to reduce such a considerable risk.

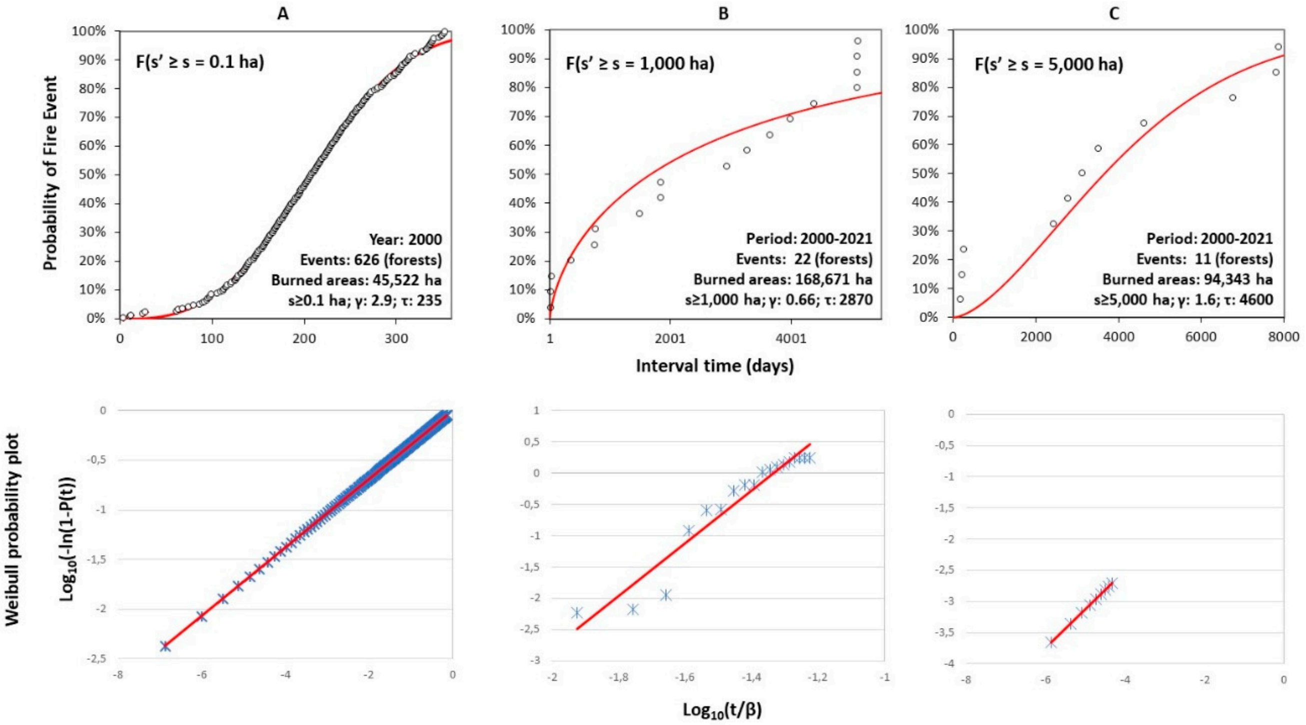


Figure 7. (**Upper row**): Indicative cumulative distribution function p(t) of recurrence times t for small (**A**), medium (**B**), and large-sized (**C**) limits of wildfires in Greece. Dots represent the distribution of observed recurrence times in various conditions. The continuous red line is the best-fit Weibull distribution with shape α and scale β parameter values per case. (**Lower row**): Weibull probability plot of the cumulative distribution of recurrence times for the data given in the corresponding panels of the upper row. The solid line corresponds to the Weibull distribution with shape γ and scaled τ parameter values per case.

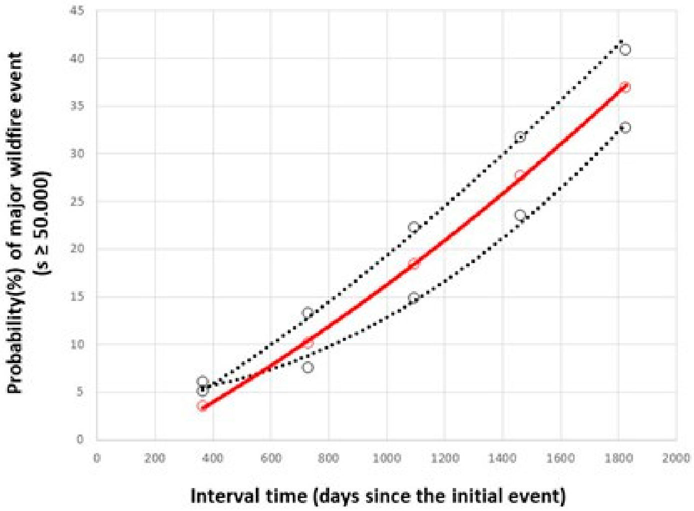


Figure 8. Conditional probability (%) (red line) of a major wildfire event in Greece, i.e., s $\geq$ 5000 ha, in the next five years. The dotted lines present boundaries of sensitivity analysis of the Weibull reliability function, with a ± 10% variation in the values of the shape α and scale β parameters of the distribution.

3.3. Automatic Linear Models of Relationships between Wildfire and Modernization Stressors

The models produced after the ALM procedure applied to the global dataset are used here to analyze the predictive relationship between the continuous variable of wildfire activity metric(s) and one or more stressors, which are continuous variables (except political competition, which is binary 0.1) (refer to Section 2.1. and Table 2 above). We assume that the predictive models, produced after the ALM all-possible-subsets approach, search the entire model space by considering all possible regression models from the pool of potential stressors. They reflect a synthetic generalization of all the factors affecting wildfire metrics. We announced 12 predictors and four quadratic and inverse transformations of GDP/cap and RES % penetration. Using the logarithmic transformation and adding non-linear interaction terms was necessary to refine the regression equation. There are a total of 2^{16} regression models (including the intercept-only model) to be automatically estimated.

According to the automated model choice procedure, the more inclusive models for the metric 'burned area' and ξi are:

$$\mathrm{Log}_{10}(\mathrm{Burned.Area}) = 29.556 - 0.004\left(\mathrm{P}_{\mathrm{anomaly}}\right) - 1.886\left(\mathrm{Log}_{10}\mathrm{RES}\right) + 7.746\left(\mathrm{Log}_{10}\mathrm{Wooded.area}\right) \tag{9}$$

$$\xi(i) = 12.173 + 0.699\left(\mathrm{Log}_{10}\mathrm{RES}\right) - 2.706\left(\mathrm{Log}_{10}\mathrm{Wooded.Area}\right) \tag{10}$$

The accuracy, i.e., the adjusted R^2 in ALM vocabulary, is 0.464 for Equation (9) and 0.335 for Equation (10). Multiple linear regressions applied to these best subsets of stressors or descriptors, with the addition of the binary variable (0,1) of Political competition (election year vs. non-election year), show significant ANOVAs (p = 0.03 and 0.026, respectively). Given the complexity of the wildfire phenomenon, lying at the intersection of multiple physical, ecological, social, and even human behavior drivers, the obtained R^2 values are satisfactory, explaining 46.4% and 33.5% of their overall variance. Descriptors of climate (precipitation anomaly), forest transition (wooded areas that include forests and afforested areas), and modernization (penetration of RES) are indeed automatically selected as the best subsets associated with wildfire metrics.

The duration of the observation period of the phenomenon adds variation to the pyrogeographic heterogeneity of Greece. Interestingly, when the effect of Political competition over the annual burned area is controlled for the extended period of 1955–2021, the linear regression model (Equation (11)) that includes the number of fires/year and the binary variable Political competition presents R^2 = 0.91.

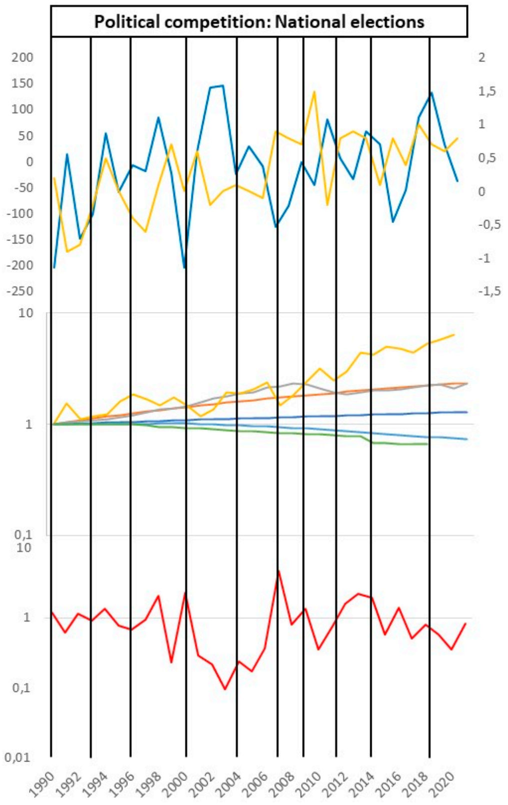
$$\mathrm{Log}_{10}(\mathrm{Burned.Area}) = 0.578\left(\mathrm{Log}_{10}\#\mathrm{Fires}\right) + 0.247(\mathrm{Pol.competition}) \tag{11}$$

It is also interesting that there is no inclusion of quadratic or inverse terms of stressors that would support the existence of non-linearities, i.e., a parabolic or hyperbolic model. A cautious interpretation of this finding would be that Greece's modernization stage lies in the falling limb of some theoretical EKC-like curve if it existed.

4. Discussion

Our approach involved modeling the occurrence frequency of small- and medium-sized fires and their scaling law to quantify the risk of large fires according to the predictions of SOC theory, at a national scale and for an extended period of years. The discussion develops around two depictions synthesizing the main findings.

The observation period of 2000–2021 is marked by the differential rate changes in the country's climatic, social, institutional, and ecological systems (Scheme 1). Although anomaly trends in meteorological factors, i.e., precipitations and average annual temperature, are discernable, influencing the duration and intensity of drought period. Remarkable changes occur in the anthropogenic component of human–nature interactions that drive the wildfire phenomenon [14,15]. As a challenge to modeling, we approached the latter under the modernization paradigm and its multi-faceted and multi-leveled human and infrastructure geographies. Narrating, i.e., explaining and predicting, the story of wildfire in Greece is bounded to time scales. Selecting the appropriate time scale is a matter of adopting the adequate paradigm in the sense of S. Pyne [11].



Scheme 1. A synthesis of the data describing the trajectories of climatic anomalies (upper panel), modernization stressors (middle stressors), wildfire severity index (lower panel), and political competition events (National elections) in Greece during 1990–2021. Color code: Upper panel: blue line: total annual precipitation anomaly (mm); yellow line: mean temperature anomaly (°C). Middle panel: yellow line: RES penetration; grey line: GDP/cap; blue line: forest area; orange line: wooded area (forest, afforested land, shrublands); green line: rural population. For comparison reasons, the middle and lower panel's actual data per measure are weighted by the corresponding value of 1990 and are log-transformed.

The ALM models (9 and 10) indicate that measures of the state of forested land and the climatic, economic, and political descriptors of pyric activity explain a significant percentage of wildfire metrics' variation. They link, in such a way, SOC statistics with SES theory [75]. The interplay between factors influencing the wildfire phenomenon's general behavior allows for various nested interpretation schemes. At an annual scale, climatic conditions explain peaks in fire severity during arid years (e.g., 2000), but fail to explain decreases in similarly dry years (e.g., 2015). Climatic conditions are rarely primary causes per se of fire ignition, but they catalyze its expansion if inefficiently suppressed at a very early stage. At the scale of the decade, the predictions of the forest transition theory [25] under modernization conditions [28], especially the reduction of the rural population and the abandonment of agricultural land, are confirmed. However, there is no evidence of a non-linear relationship with modernization descriptors, such as the penetration of Renewable Sources of Energy or GDP/cap growth. This empirical finding corroborates earlier findings on deforestation rates (primarily tropical), rejecting the U-shape EKC hypothesis, i.e., the inversion of forest decline through policies affordable under high-wealth conditions [18,32,52,53].

The SOC fire frequency–magnitude and time interval statistics add some interesting complements to the above typical summarization of trends. For instance, (1) the number of individual events is expected to increase in the following years; (2) most of the fire ignitions are in wooded lands and not in forests per se; (3) most large-sized wildfires affect mosaics of landscape, i.e., afforested patches, shrublands, agricultural land, and forest remnants; (4) fire suppression operations seem successful in the majority of cases and years, as the estimated γ-scaling factor suggests in comparison to published values in other countries or periods [39,41,51].

However, the striking finding relates to the wildfire phenomenon as significantly associated with enabling political factors, such as competitive elections. Eventually, as we extend the time scale backwards till 1955, i.e., the year since continuous data series of wildfire metrics existed in Greece, the fire-enabling repercussions of political competition become even more apparent. Elections per se are but a proxy of government and governance procedures. Evidence for a 'political cycle of fire' has already been reported in Greece [76,77]. Further, the literature offers several examples of unavowed social bargaining incentivizing politicians and encouraging the electorate to trade permission for forest preservation policies' retraction in return for political voting and support [32,78–80]. Although the literature on this condition of bad governance is often limited to corruption, deceit, or unfair legislation [81], we consider that the violation of the central or acceptable norms of good practices in environmental policies encompasses important aspects of institutional deficit in Greece, primarily in spatial planning, land-use mapping, and land-property cadastral [82].

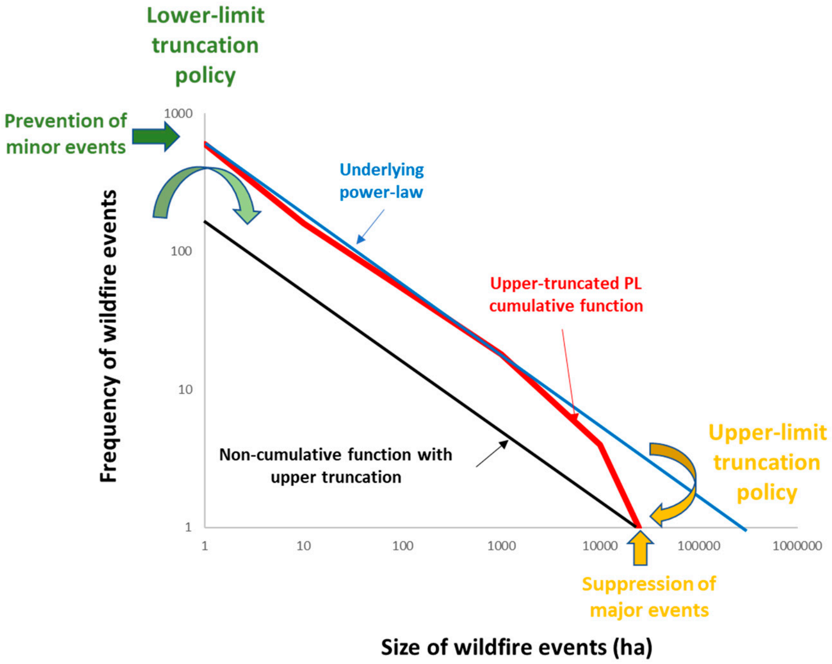
For example, one should note that the re-regulation of vegetation types' characterization (forests vs. naturally afforested lands) was adopted in 2022. The intriguing part is that it figures within the National Plan on Prevention of Corruption (L 4915/2022), whose corruption one might wonder, and not in some environmental legislation.

There is no misunderstanding here: institutional deficit does not mean loopholes in the environmental and forest laws' provisions. On the contrary, the complexity per se and inherent contradictions of the environmental legal framework lead to legal indeterminacy, normative ambiguity, and regulatory uncertainty. With the intricate skein of Command-and-Control authorities or agencies, the institutional deficit is generated at various forest governance and operations levels. As early as 2001, Sapountzaki and Karka [83] diagnosed "*. . . The main conclusion is that for the time being, sustainability objectives in strategic and top-down spatial planning in Greece rather perform the function of a political manifesto and 'legalize' traditional weaknesses than drive real development towards a sustainable course. The chances for operational success are expected slim shortly and originate mostly from the European Union (EU) political and economic pressures, producing however fragmented, single-dimension results for which commitment of the involved societies has never been accomplished and confirmed . . .* ". Complementary to the previous, the issue of active management within conservation-designated forests or forested areas, e.g., National Parks or Natura 2000 SCI, remains untouched. Greece allocated a huge *ca* 27% of its land territory to conservation. Apostolopoulou and Pantis [84] stated, "*. . . lack of clear goals, and divergences between stated and actual goals led to bureaucratic interpretations of conservation objectives and distortion of decision processes in favor of satisfying economic and development interests . . .* ".

The all-too-late ongoing publication of forest maps for half of Greece's territory (2020–today) shows that 60% of the corresponding land is forested, which is an 8.2% increase since the baseline year of 1945. These public domain findings confirm the forest transition process. The published forest maps and forested cadastral areas correspond to 3.62 million ha, of which >0.25 million are contested by >330,000 individuals, claiming property rights, and negating the forest character of their abandoned property. In other words, almost 6% of this forested area is of undefined property or official vegetation type designation. Claimed surfaces are falling to 5–10 m^2, especially in touristic real estate value areas. One would legitimately suspect that one cause of such a high frequency of small-sized wildfire events might lie in land-claiming arsons.

Scheme 2 synthesizes the ongoing debate in Greece, i.e., prevention vs. suppression of wildfires, within the unified framework of SOC theory under modernization transitions.

Recently, the Independent Committee of the Global Fire Monitoring Center (IC/GFMC) [85] published a report on 'Underlying Causes and Perspectives for the Future Management of Landscape Fires in Greece.' One can find an extensive enumeration of various social and misgovernance causes of the evolution of the wildfire phenomenon in the country. One will also find a generalist framework for proactive policymaking based on the typical traits of any good-practiced policy, such as coherence, coordination, data gathering, monitoring, or innovation. In a SOC-like vocabulary, prevention might be called 'low-limit truncation policy' and suppression, 'upper-limit truncation policy', respectively. It might be pompous enough that they crystallize wildfire policy goals and targets: reduction of the frequency of small-sized fire events vs. reduction of the size of large ones. SOC theory predicts the relationship between them in time and space. Presumably, almost any early suppressed events could have evolved into significant events under slightly different conjectural conditions. Targeting the suppression of major wildfire events passes through the control of initial ignitions.



Scheme 2. A synthesis of the predictions of SOC theory for the fire frequency–magnitude PL relationship and the corresponding wildfire management policies.

Then, the real challenges for environmental and forest policymakers emerge. It is not an issue of reallocating funds between preventive and suppressive fire activities. It is the continuous, repetitive, and mandatory forest and fuel management activities and works, arson policing, and forest criminality prosecution vs. the episodic operational fire-fighting efficiency. The first challenge in this domain is whether wildfire management should be cost-efficient (i.e., the degree to which resource use is minimized for achieving given fire abatement targets or target achievement maximized for a given resource level, regardless of how targets are defined) or cost-effective (i.e., a measure of abatement achievement per cost considering wildfire occurrence patterns and causes, rather than ignoring both).

The second challenge relates to the question of, or need for, proactive forestry intervention in protected forested areas, e.g., maintenance of forest roads or withdrawal of excessive biomass. Bizarre as it might be, the stake is the cultural symbolism of 'pristine nature'. How this symbolism is used or misused by various stakeholders involved in the public wildfire management debate often mediates a perversely comforting portrait of nature. The scientifically unfounded ideation of "no human activity" in conservation areas absolves political elites from bad environmental practices and local forest authorities from the responsibility of constantly enacting good management practices on the ground. It also makes long-term changes in the public's mentalities and perceptions more difficult to evolve. For example, adaptive wildfire strategies, such as prescribed burning [86–88] or genomics-based assisted migration of less-flammable species in forest plantations [89], are marginally discussed publicly in Greece.

However, nothing above makes sense if the 'political cycle of fire' is not disrupted. The wildfire interval time is a probabilistic approach to risk in time. As in other geophysical hazards, e.g., earthquakes or avalanches, such a probability does not refer to an exact time or location prediction. However, it can predict that a large 'disastrous' wildfire, a mega-fire, is almost inevitable in the scale of the decade or within the mandate of two successive governmental periods (Figure 8). As Wilson et al. [90] analyzed, there is a disconnect between the desired wildfire prevention and suppression tandem and what they call the "politically possible" in wildfire management. It requires agreement among stakeholders with different and often conflicting values, benefits, or costs affected by actions and policies. It certainly requires the severe curving of partisan conflict over natural disasters for rational, proactive, and even unpopular policies to be steadily implemented. This interplay between the political possible vs. feasible applies to almost every domain of environmental governance, where spatial planning might influence land property rights or monetary aspects of the real estate market. The ongoing debate on land price-determining vs. price-determined valuation [91] sets a stringed corridor for non-opportunist or case-specific wildfire management decision-making.

5. Conclusions

This contribution supports the feasibility of combining SOC theory and modernization statistics to explain and predict wildfire trends. This approach might offer elements for analyzing the efficiency of wildfire management policies in setups where the combination of physical, ecological, social, and political pressures upon the ecosystem drive forest recovery going up in smoke.

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Appendix A

Data series on fire events, i.e., location and timing of ignition, size of burned areas per vegetation type, as well as those of a series of stressors, i.e., We used the best available data sources, e.g., the United Nations (UN), World Bank (WB), the Organization for Economic Cooperation and Development (OECD) databases, as well as Greece's Statistical Authority (ELSTAT), Forestry Service, Hellenic Fire Fighting Corps, and Ministry of the Interior databases. The various variables' and indicators' data series range from 1955 to 2021. Notice that the standard unit for the surface in Greece equals 0.1 ha (1000 m^2): land value, real estate transactions, agricultural subventions, and burned areas are expressed per this unit, called stremma. This unit allows for higher resolution in land measurements; for instance, fire records as small as 0.1 or 0.01 stremmas. However, hereafter, all comparisons are based on hectares after binning all records <1 stremma to 0.1 ha.

Table A1. Synopsis of variables used in calculating fire frequency vs. size of burned areas and the models' relationship with material macro-structural aspects of modernization. FS: Forestry Service; (a) HFFC: Hellenic Fire Fighting Corps; (b) EFFIS: European Forest Fire Information System; (c) WB: World Bank; (d) UN: United Nations Population Division; (e) FAO: Food and Agriculture Organization; (f) OECD: Organization for Economic Cooperation and Development; (g) IEA: International Energy Agency; (h) ELSTAT: Hellenic Statistics Authority; (i) MoI: Ministry of the Interior (Greece); (k) meteoblue (m).

Variables	Range	Type of Data	Units	Source	Remarks/Definitions
Wildfires					Forest.area_x differs according to the institutional regime of 'forest' adopted in successive years. Wooded. Areas comprise forests, afforestation areas due to abandonment, plantations and tree cultivations, and shrublands.
Forest.area_1	1955–2021	Numeric, count Burned area, ignition time, duration of the event, interval times	10^3 m^2, ha	a	
Forest.area_2	2000–2021		10^3 m^2, ha	b	
Wooded.areas_3	2000–2021		10^3 m^2, ha	c	
Number of fire events	1955–2021	Numeric, count	# fires	a b c	All fire events recorded
Modernization					
Population	1960–2021	Numeric, count Census of population	10^6 ind #ind/km^2	e, f, h	Population density is midyear rural or urban population divided by the corresponding land area in square kilometers.
Urb.pop_dens					
Rur.pop_dens					
RES/Hydro in energy mixture	1990–2021	Numeric, count	%	g	% energy produced by Renewable Energy Sources and Hydropower plants
Agricultural.land% *Wooded.land%*	1961–2018 1990–2020	Numeric, count Agricultural statistics	% Territory	d, g	Agricultural land is the share of arable land under permanent crops and pastures. Forest area is land under natural or planted trees of at least 5 m in situ.
GDP/cap_PPP	1990–2021	Numeric, count Economic statistics	Current $	d, h	Per capita values for the gross domestic product in current international $ converted by purchasing power parity (PPP) conversion factor.
Energy.consumption/cap	1960–2014	Numeric, count Energy statistics	kWh/cap	d, i	Production of power plants and combined heat and power plants less transmission, distribution, and transformation losses and use by heat and power plants.
Automobile fleet	1985–2020	Numeric, count	Number	h	Total of cars, trucks, motorbikes
Political risk	1955–2021	Nominal	Y/N	i	General elections for the Parliament
Climate change anomalies	1979–2021	Numeric, count	dimensionless	k	Deviations of Temperature and Precipitation from the 30-year average.

FS: Forestry Service (a): https://geodata.gov.gr/group/86b07ab4-4ee6-4d66-a5da-1f849cdaa0f5?organization=ypapen; HFFC: Hellenic Fire Fighting Corps (b): https://www.fireservice.gr/el/synola-dedomenon [in greek legends]; EFFIS: European Forest Fire Information System (c): https://effis.jrc.ec.europa.eu/applications/data-and-services; WB: World Bank (d): https://data.worldbank.org/country/GR; UN: United Nations Population Division and FAO: Food and Agriculture Organization (e,f): https://data.un.org/en/iso/gr.html; https://www.fao.org/faolex/country-profiles/general-profile/en/?iso3=GRC; OECD: Organization for Economic Co-operation and Development (g): https://www.fao.org/faolex/country-profiles/general-profile/en/?iso3=GRC; IEA: International Energy Agency (h): https://www.iea.org/countries/greece; ELSTAT: Hellenic Statistics Authority (i): https://www.statistics.gr/el/home/SDG15_22_11_2022_GR.xlsx; MoI: Ministry of the Interior (Greece) (k): https://www.ypes.gr/statistika/; meteoblue (m): https://www.meteoblue.com/el/climate-change/greece_%ce%97%ce%a0%ce%91_5119251. (all accessed on 13 July 2022).

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