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Key Points:
- A new fire model is based on the feedback between fuel abundance and fire
- Land abandonment drives the Mediterranean forest to different fire dynamics
- Wildfire regime sequence is robust along the land development gradient

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Wild forest fire regime following land abandonment in the Mediterranean region

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Abstract Land use, climate, and fire have markedly shaped Mediterranean ecosystems. While climate and land use are external forcing, wildfire is an integral component of ecosystem functioning which inevitably poses a threat to humans. With a view to gaining an insight into the mechanisms underlying fire dynamics, fire control, and prevention, we formulated a model that predicts the wildfire regime in fire-prone Mediterranean ecoregions. The model is based on the positive feedback between forest expansion following cropland abandonment, fuel abundance, and fire. Our results demonstrate that progressive land abandonment leads to different fire dynamics in the Mediterranean forest ecosystem. Starting at a no-fire regime when the land is almost completely cultivated, the ecosystem reaches a chaotic fire regime, passing through intermediate land development stages characterized by limit cycle fire dynamics. Wildfires are more devastating, albeit more predictable, in these intermediate stages when fire frequency is higher.

1. Introduction

Climate, geology, and fire have jointly shaped Mediterranean ecosystems and influenced their soil-vegetation evolution [*Paula et al.*, 2009]. Fire disturbs the hydrological and erosional processes evolving in a certain landscape [*Cerdà*, 1998] and increases solute release [*Lasanta and Cerdà*, 2005], leading to changes in soil characteristics [*Martin et al.*, 2012; *Guénon et al.*, 2013]. Moreover, postfire soil treatments aimed at favoring vegetation recovery and reducing soil loss also alter ecosystem balances of energy and matter [*Fernández et al.*, 2012] and their spatial [*Bodí et al.*, 2013] and temporal [*Pereira et al.*, 2014] distributions. Fire is part of the landscape evolution in the Mediterranean-type climate and, at the same time, poses a threat to humans [*Moreira et al.*, 2011]. The Mediterranean region is highly vulnerable to forest fire after land abandonment both because of the low social and economic capacity to adapt to the changing economic conditions [*Lindner et al.*, 2010], and local climatic conditions that are characterized by decadal-scale drought, converting potential into available fuels [*Verdon et al.*, 2004]. Policies should set up and develop forest fire mitigation and adaptation strategies [*Carreiras et al.*, 2014]. The cross interactions between vegetation, soil, climate, and fire are still partially unexplored, especially in land use change scenarios. In order to compare and implement fire control and management strategies, the statistics of timing, frequency, and magnitude of Mediterranean wildfire need to be linked to the processes involving soil water movement, vegetation dynamics, and climate variability [*Rodrigo et al.*, 2004; *Cui and Perera*, 2008]. Below, forest is modeled as a system of two superimposed layers [*Casagrandi and Rinaldi*, 1999]. This distinction has a particular meaning when simulating wildfires and their dynamics in zones subject to a Mediterranean climate. Typical Mediterranean woodlands (e.g., chestnut or pine forests) often have a relatively rich understory, usually shrubs showing a high potential for fire. Shrubs recover relatively rapidly, and they develop enough biomass to be burnt again within 2–5 years after fire [*Cerdà*, 1998; *Cerdà and Doerr*, 2005]. Therefore, the distinction made in our model may also provide insights into the effect that a disturbance in the forest overstory (wildfires or prescribed fires) exerts on the understory, and vice versa. Outcomes of such a modeling framework can help ascertain the time span required for the understory to stabilize after a fire and thus affect the evolution of diverse ecohydrological processes such as insect proliferation and soil erosion.

Global change, in general, and land use change, in particular, appear to be responsible for major changes in the fire regime, which is often attributed to forest fuel accumulation [*Dodge*, 1972; *Rego*, 1992; *Pechony and Shindell*, 2010; *Pausas and Fernandez-Muñoz*, 2012]. Two-predators-two-pray (TPTP) models may predict the fire regime induced by fuel abundance and aridity [*Ursino and Rulli*, 2011]. Vegetation flammability and the fire extinction rate characterize different fire ecoregions including the Mediterranean forests [*Casagrandi and Rinaldi*, 1999]. Climate generates different fire dynamics in the Mediterranean forest ecosystem of TPTP, including the static point, the limit cycle, and chaos [*Ursino and Rulli*, 2011], according to experimental evidence [*Peterson*, 2002].

The abandonment of terraces can often cause an increase in gully erosion, resulting in landslides and loss of fertile soils [*Tarolli et al.*, 2014; *Arnaez et al.*, 2011], even though revegetation following land abandonment may positively affect soil water-holding capacity and soil recovery [*Cerdà*, 1997] but may also increase net soil losses and total erosion rates [*Debolini et al.*, 2013]. Reforestation contributes to the recovery of wildlife, but the sudden encroachment of shrubs leads to increased risk of wildfires [*Vázquez and Moreno*, 2001].

Statistical analysis of the wildfire regime reinforces the role of fire as a determinant of ecosystem shape and functioning [*Corral et al.*, 2008; *Lasaponara et al.*, 2005]. Several authors found a good correlation of the frequency-area distribution of wildfires with a power law [*Ricotta et al.*, 2001; *Malamud et al.*, 2005] in Mediterranean and non-Mediterranean ecoregions where the power law exponent changes with forest fragmentation and human population density. In self-organizing systems, small ignition sources can evolve into fires of any magnitude [*Bak*, 1996]. Forest models, which are examples of self-organized criticality, produce the observed power law behavior and indicate what might be the possible underlying process fingerprint [*Malamud et al.*, 1998]. Human control over fires, land use practices, and other human interventions further affect the distribution of wildfires [*Turcotte*, 1999].

Within the above discussed issues, the significance of fire suppression [*Ward et al.*, 2001; *Miyanishi and Johnson*, 2001], land history [*Schoennagel et al.*, 2008; *Moghaddas and Craggs*, 2007] and human influence [*Syphard et al.*, 2007; *Turner*, 2010] are still the subject of debate. To investigate the risks of agricultural land abandonment, the resulting forest land expansion and related fuel accumulation, and hence the fire regime dynamics across a land abandonment gradient, we formulated a nonspatial model combining Tilman's approach for structured habitats [*Tilman*, 1994] and TPTP approaches [*Casagrandi and Rinaldi*, 1999]. The model that we present in this paper is not an upgrade of already available frameworks. The crop-forest fire dynamic model is novel and provides answers to the question whether and how land use may alter the forest fire regime. Similar to *Ursino and Rulli* [2011]'s model, we account for the different behavior between the overstory and understory plant species. In our study the above two types of plant species occupy a progressively increasing fraction of total available land due to agricultural land abandonment, leading to an increase in both forest land cover, species continuity, fuel accumulation, and hence to burning-prone situations. Crops are modeled as superior competitors that do not change their land occupancy spontaneously and act as a barrier to forest expansion. Cropland occupancy becomes a control parameter in the balance equations governing forest fires, accounting for the retreat of the cultivated land fraction in favor of the forested land fraction. There is evidence that progressive abandonment of rural areas and the crops concerned induces a different fire dynamics in the Mediterranean forest ecosystem, and our study not only provides a physically based explanation for this experimental evidence but further suggests what may be the impact of this complex man-and-nature-driven land evolution on the forest composition and the soil moisture budget between the no-fire regime occurring in intensive agriculture and the chaotic fire regime that may characterize self-regulating forest fires when land abandonment is almost complete [*Ursino and Rulli*, 2011].

We specifically focus on a single typical ecoregion and emphasize the need for consideration of coexisting cropland and forest-use land in order to distinguish relevant fire features and underlying processes. The analysis of fire dynamics as a result of fuel production and climate may help illuminate which fire control strategies could be most effective at the various stages of the land use change process.

2. Model

The forest site occupancy in a nonspatial model (Figure 1) is restricted by crop and fire, and the fire regime is dictated by fuel abundance and thus forest occupancy.

According to Tilman's multispecies dynamics [*Tilman*, 1994], forest and agricultural lands are modeled as individuals with colonization limitations, each existing at discrete points in space. Crops represent a physical barrier to forest colonization and do not change their land occupancy spontaneously unless changes in land use occur.

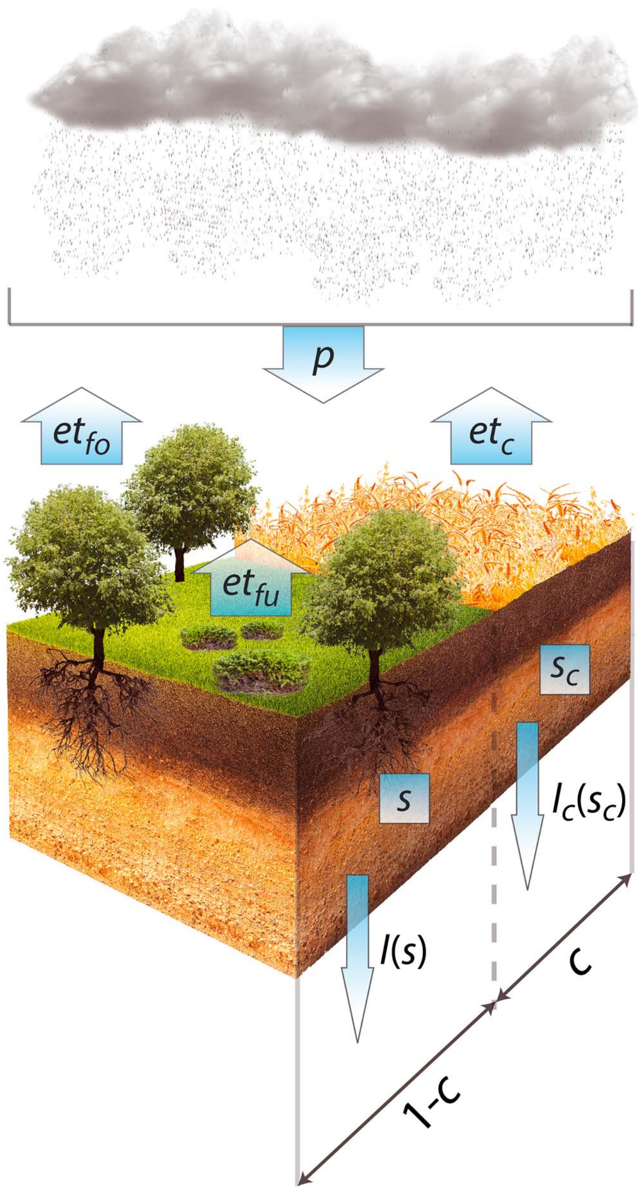

Figure 1. Schematic representation of the conceptual model, showing the main variables used in this study.

The interrelation among land use, irrigation strategy, water resources management, and climate is complex and seldom easy to make explicit [*Federman et al.*, 2013]. For the sake of simplicity we restrict our analysis to the case of precipitation (p) and irrigation (i) compensating for crop evapotranspiration (et_c) on an annual basis. In this case, leakage l_c out of the cropland control volume is negligible.

$$\frac{\partial s_c}{\partial t} = p + i - \mathrm{et}_c \cdot c = 0 \tag{1}$$

where s_c is the cropland soil moisture. The assumption that subsurface lateral moisture exchange between forest and cultivated land is negligible allows us to decouple the cropland soil moisture balance (equation (1)) and the forest-land soil moisture (s) balance without substantial lack of generality. Also, the fire-free crop dynamics is not explicitly described in the model, and cropland occupancy c becomes a control parameter to forest dynamics.

Forest overstory and understory occupy the same fraction of land although the overstory is a superior competitor for light [*Casagrandi and Rinaldi*, 1999]. Land abandonment and fire provide an opportunity for the two forest species to colonize new openings.

The model describes the soil moisture and vegetation dynamics at regional scale and consists of the following five dimensionless ordinary differential equations

$$\frac{\partial s}{\partial t} = \left(p - q(p, b_o, b_u) - \mathrm{et} - l(s)\right) \tag{2}$$

$$\frac{\partial f_o}{\partial t} = f_o\left(1 - c - f_o\right) - \left(\beta_o \frac{f_o}{f_o + h} \cdot b_o - \gamma_o \frac{f_o}{f_o + h} \cdot b_u\right) f(s) \tag{3}$$

$$\frac{\partial f_u}{\partial t} = \mathrm{gr} \cdot s \cdot f_u\left(1 - c - f_u\right) - \alpha f_o \cdot f_u - \left(\beta_u \frac{f_u}{f_u + h} \cdot b_u - \gamma_u \frac{f_u}{f_u + h} \cdot b_o\right) f(s) \tag{4}$$

$$\frac{\partial b_o}{\partial t} = \left(\beta_o \frac{f_o}{f_o + h} \cdot b_o - \gamma_o \frac{f_o}{f_o + h} \cdot b_u\right) f(s) - \delta_o\, b_o \tag{5}$$

$$\frac{\partial b_u}{\partial t} = \left(\beta_u \frac{f_u}{f_u + h} \cdot b_u - \gamma_u \frac{f_u}{f_u + h} \cdot b_o\right) f(s) - \delta_u\, b_u \tag{6}$$

Table 1. Model Dimensionless Parameters

Parameter	Parameter Value	Definition
		Water Balance Equation [*Ursino and Rulli*, 2011]
p	0.03–0.09	dimensionless effective rainfall
φ	0.5	runoff coefficient
χ	0.01	negative environmental moisture content and fire feedback coefficient
et_{f_o}	0.0125	overstory reference evapotranspiration
et_{f_u}	0.0125	understory reference evapotranspiration
l_e	0.04	reference leakage
γ	3	leakage coefficient
		Biomass Dynamics [*Casagrandi and Rinaldi*, 1999]
gr	6	ratio between understory and overstory colonization rates
α	2	interspecific competition coefficient
		Fire Dynamics [*Casagrandi and Rinaldi*, 1999]
β_o, β_u	100	intraspecific fire attack rate
γ_o, γ_u	0.4	interspecific fire attack rate
h	0.015	half-saturation burning constant
δ_o, δ_u	85	burning biomass extinction rate
k_r	1	positive direct runoff and fire feedback coefficient

where s ($0 \le s \le 1$) is the forest soil moisture saturation, f_o [$0 \le f_o \le (1-c)$] is the forest overstory land occupancy, f_u is the forest understory land occupancy, whereas b_o and b_u are burning biomass land occupancy of the two forest species, respectively. Dimensionless time, $t = \tau \cdot \mathrm{gr}_o$, is current time, τ, times overstory growth colonization rate, gr_o, which corresponds to the postfire regeneration rate. The regeneration rate of the understory is $\mathrm{gr}_u = \mathrm{gr} \cdot \mathrm{gr}_o$. The dimensionless net water flux entering the soil control volume, namely, the difference between the dimensionless annual average values of precipitation, p, and direct runoff, q [i.e., the term $(p-q)$], represents one of the two main ecosystem drivers, leading the soil moisture and biomass to different steady states and the TPTP system to different fire regimes. The other main driver is the land use described through cropland occupancy, c. Seasonal and interannual variations of p are not modeled explicitly (as, for example, in the work by *Romano et al.* [2011]), and therefore, the forest soil moisture dynamics is driven by vegetation and fire.

Table 1 reports the definition and values of dimensionless model parameters. When $c=0$ the model substantially reduces to a dimensionless form of the ecohydrological fire model proposed by *Ursino and Rulli* [2011].

Runoff may increase considerably in the postfire scenario, due to fire-induced soil water repellency of the surface soil [*De Bano*, 2000; *Seibert et al.*, 2010]. Therefore, we assume that [*Ursino and Rulli*, 2011]

$$q = p\left[\varphi + (1-\varphi)\cdot\frac{b_u + b_o}{b_u + b_o + k_r}\right] \tag{7}$$

where φ is the no-fire runoff coefficient and k_r is an environmental effective parameter accounting for the feedback between direct runoff and fire.

The soil moisture balance (2) accounts for evapotranspiration of each species, since

$$\mathrm{et} = \mathrm{et}_{f_o}\ f_o + \mathrm{et}_{f_u}\ s\, f_u \tag{8}$$

We assume here that forest understory is much more sensitive to water stress in the postfire scenarios when soil water repellency induces a temporary moisture deficit which, in turn, affects evapotranspiration flux and growth rate. Instead, the activity of the forest overstory depends less on the degree of soil moisture saturation of the forestland soil control volume since woody species generally have relatively deep root system architectures and soil water availability from deeper soil layers is less affected by fire-induced runoff fluctuations [*Brooks et al.*, 2010].

Assuming a unit gradient of the total soil water potential, leakage out of the forestland control volume, $l(s)$, can be set as a power function of forest soil moisture saturation s as follows

$$l = l_e(s)^{\gamma} \tag{9}$$

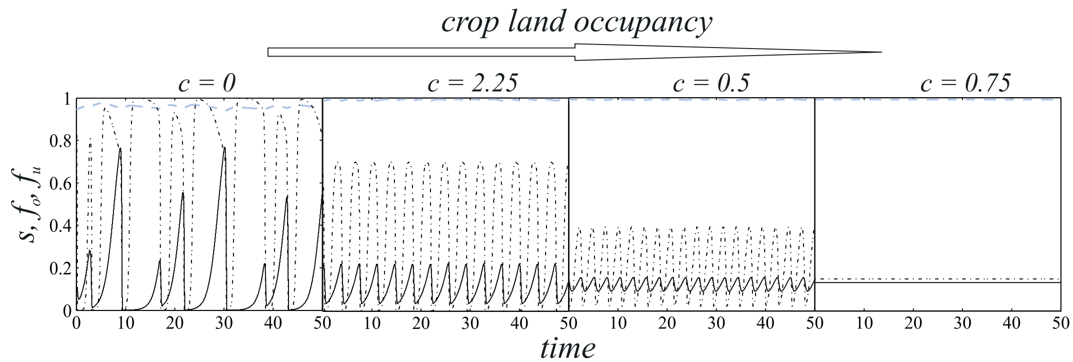

Figure 2. Temporal evolution of the dependent variables s, f_o, and f_u for $p = 0.9$ and different crop land occupancy, namely, $c = 0$, 0.25, 0.5, 0.75. Continuous line: overstory biomass density (f_o); dashed black line: understory biomass density (f_u); dashed blue line: soil moisture (s).

where l_e is a dimensionless reference leakage and γ is a parameter depending on soil type.

Soil moisture is taken as a proxy of the environmental moisture content, with a negative feedback between soil moisture, s, and fire, which is described by the following relation

$$f(s) = (1 - s)^{\chi} \tag{10}$$

where $f(s)$ is a fire ignition reduction function and χ is an environmental effective parameter accounting for the negative feedback between environmental moisture content and fire.

Below we will restrict our discussion to the dimensionless model outcome only. However, it is worth noting that the dimensionless results may translate into very different dimensional fire regimes depending on the site-specific scaling factor gr_o and the land area. Indeed, the reciprocal of the postfire overstory regeneration rate scales the fire frequency. This means that resprouting ability is a key factor in fire-prone environments that links the ecoregion characterization to the fire frequency. The maximum forest land occupancy $(1 - c)$ determines the upper limits of the fire magnitude and the area burned that is often related to fire frequency.

3. Results

Land abandonment leads to forest land expansion, increasing fuel production, and a changing wildfire regime. Different stages of land abandonment are simulated as a sequence of land development stages with progressively increasing cropland occupancy (c). The impact of land use on the Mediterranean wildfire regime is illustrated in Figure 2, where the temporal evolution of the computed variables f_o and f_u are plotted for $p = 0.09$ and $c = 0$, 0.25, 0.5, and 0.75 (left to right).

Figure 3 shows the corresponding power spectral density (PSD) of the fast Fourier transform for variable $f_o(t)$. Fire is chaotic for $c = 0$ according to previous findings [*Ursino and Rulli*, 2011], whereas the coexistence of cropland and forests regularizes the fire regime and forces the system toward a stable cycle through restricting the fuel production. Starting at a no-fire regime, for $c \leq 0.75$ the PSD of the overstory biomass time series exhibits an increasing multiplicity of peaks (depicted by the red circles of Figure 3) as land abandonment progresses (right to left).

At steady state, in the absence of fire, the overstory's land occupancy is $(1 - c)$ and the understory's is $(1 - c) \cdot \left[1 - \alpha \cdot (s\ \mathrm{gr})^{-1}\right]$. To demonstrate the impact of fire on the forest ecosystem, Figure 4 compares the no-fire forest steady state with the computed average soil moisture level (circles) and biomass density (continuous and dashed lines for the overstory and understory layers, respectively). Each point corresponds to a different stage of land abandonment, i.e., different c values. Even though the model does not account for fire selectivity [*Barros and Pereira*, 2014], it does link fire preference to fuel availability and thus indirectly to the life history traits of each species. The understory biomass density is indeed less affected by fire due to the faster resprouting behavior of the understory species (see the dashed lines in Figure 4). Instead, fire restricts forestland occupancy and exerts a major impact on the overstory component (see the continuous lines in Figure 4). Following the no-fire regime when the no-fire steady state solution $1 - c$ and the average calculated biomass density f_o coincide at any time, as c decreases, fire causes a sudden reduction in f_o in the

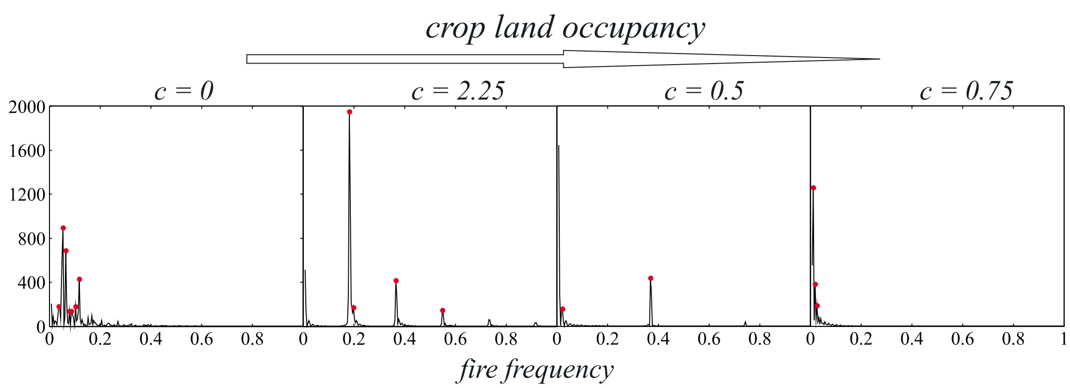

Figure 3. Power spectral density of fast Fourier transform of overstory biomass density (f_o) time series for $p = 0.9$ and different crop land occupancy, namely, $c = 0$, 0.25, 0.5, 0.75.

limit cycle fire regime. As the fire regime approaches a chaos condition the average f_o starts to draw closer to the steady state no-fire solution.

The Mediterranean-type climate is characterized by summer drought that rapidly transforms biomass into fuel. Different climate scenarios are simulated by changing p, i.e., the parameter that dictates the average availability of water resources (adverse years with long dry summers are not considered because our focus is on a fuel-dominated fire regime). The case $p = 0.09$, corresponding to Figures 2 and 3 , is shown in the right-hand panel. Smaller soil moisture availability, corresponding to greater potential water stress, leads to an earlier switch to a chaotic and less destructive fire regime as land abandonment progresses and c decreases (the switching points of the fire regime are highlighted in Figure 4 by bold circles).

The fire frequency corresponding to the maximum PSD of f_o and f_u is referred to in the following as *fire frequency*. As land abandonment progresses and the system approaches the forest closure, multiple peaks appear and the fire regime can evolve into a fire of any magnitude, without one is being able to identify a characteristic fire frequency (Figure 3). In Figure 5 the average and standard deviation of f_o and f_u are plotted against fire frequency for different c and three p values.

The average biomass density is an estimate of forest development and fuel abundance. The standard deviation of biomass density is a measure of fire impact on the ecosystem and of fire severity. The impact of fire on the environment, fire size, and average annual area burned is primarily determined by fuel abundance and flammability. Data plotted in Figure 5 were obtained for c ranging from 0.05 to 1. Different points correspond to different stages of land abandonment. There is a negative correlation between f and the standard

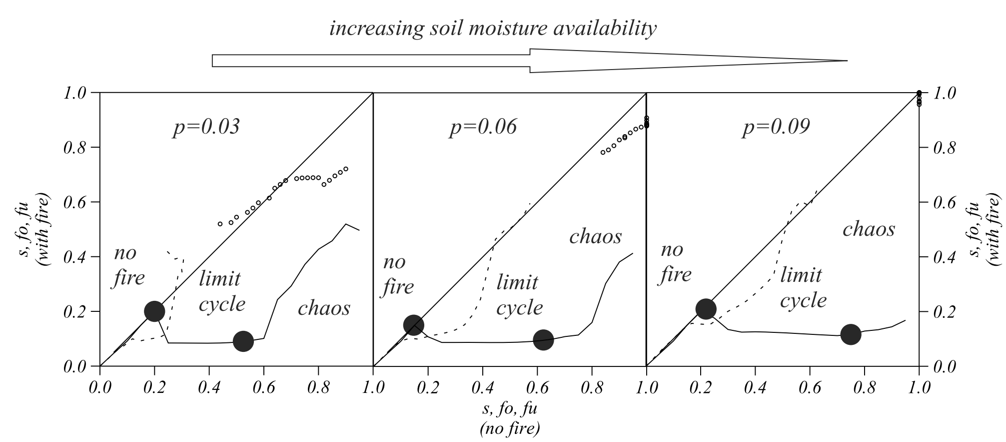

Figure 4. Steady state solution obtained in the absence of fire versus annual average of the three dependent variables f_o, f_u, and s, for different stages of land development, and three average annual precipitation values p. Continuous line: no-fire steady state overstory biomass density versus average f_o; dashed line: no-fire steady state understory biomass density versus average f_u; circles: no-fire steady state soil saturation versus average s. Left to right: $p = 0.03$, 0.06, 0.09. Bold circles indicate the switching points of the fire regime.

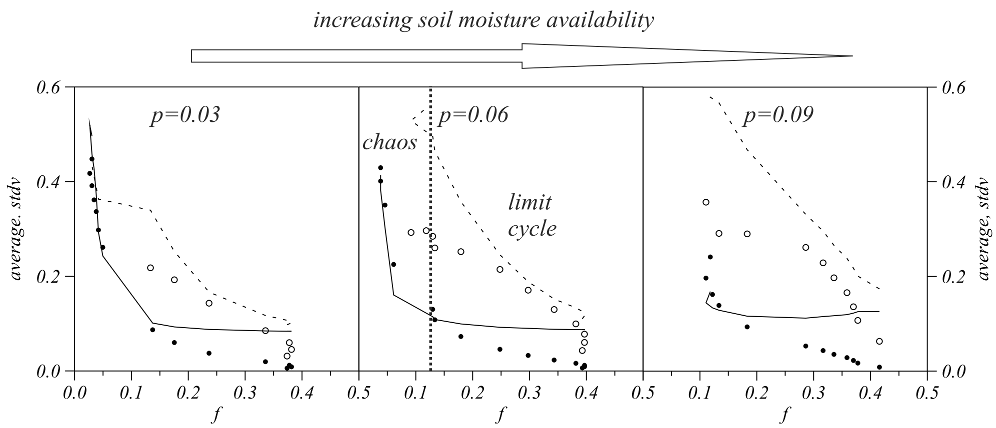

Figure 5. Standard deviation and average f_o and f_u versus fire frequency, for different stages of land development, and three average annual precipitation values p. Continuous line: average f_o; dashed line: average f_u; bold circles: standard deviation of f_o; open circles standard deviation of f_u. p = (left) 0.03, (middle) 0.06, (right) 0.09.

deviation of $f_o(t)$ and $f_u(t)$, meaning that as fire frequency decreases, the average area burned increases. More frequent fires occur at low average biomass density and thus are less destructive (causing less biomass losses).

Figure 5 compares the cases $p = 0.3$, 0.6, and 0.9 (from left- to right-hand panels, respectively). Soil moisture scarcity (increasing with decreasing p) limits the understory biomass growth and the fuel production of the faster resprouting species, leading the system to an earlier chaotic fire regime (Figure 4). In the case $p = 0.3$, the fire frequency is always low; forest development and fire severity are limited by the low fuel production. As shown in Figures 5 (middle) and 5 (right) (corresponding to $p = 0.6$ and 0.9, respectively), larger p values result in larger fuel production and a more severe impact of fire on the ecosystem.

Climate, water resources management, and irrigation strategy, which become ever more closely interwoven in Mediterranean regions, have an impact on the net soil moisture income, the forest development, and indirectly on the fuel-dominated fire regime. Figures 4 and 5 demonstrate that for a typical ecoregion the correspondence between the stage of land abandonment and fire regime is robust with respect to climate. For all of the three cases $p = 0.03$, 0.06, and 0.09, as the land abandonment progresses the wildfire regime switches rapidly from a no-fire regime to a periodic and finally chaotic fire regime.

4. Discussion

According to our conceptual model, an increase in fuel abundance, as a consequence of an increase in land abandonment, is predicted to cause a sudden increase in fire frequency. However, as the forest approaches its closure, the ecosystem self-regulates and dictates the fire regime, reaching higher biomass densities in the chaotic fire regime. This result partly conflicts with the experimental evidence gained in a few zones where an increased number of fires and burned area were attributed to a reduction in agricultural practices [*Pausas and Fernandez-Muñoz*, 2012; *Keeley et al.*, 2012]. This situation may also be due to the fact that adverse weather conditions and fire suppression may far outweigh the importance of average fuel availability, which might not be the cause of the observed fire regime switch.

A certain lack of correspondence between simulated and real-world situations may also be attributed to several other fire drivers that are not modeled here. Fire often alters the fuel structure and favors the colonization of fire-adapted invasive species [*Brooks et al.*, 2004; *Keeley and Brennan*, 2012] and the formation of a heterogeneous mosaic of species and age classes, acting as patterns of fuel accumulation [*Minnich*, 1983]. As we referred to a typical two-layer Mediterranean forestland, any change in the vegetation life history trait was ignored. We may conjecture that the appearance of fast resprouting species in the postfire scenario may completely reverse this trend. Fire frequency and intensity are linked to the growth rate and carrying capacity of the species. Hence, fast resprouting invasive species may also affect the fire regime following a land use change. An issue that deserves further exploration is whether and to what extent a change in species composition may completely overturn the self-organization of a fire-prone forest. Our results are presented in dimensionless form for static vegetation life traits. Linking the dimensionless fire frequency to its scaling factor would emphasize that increasing postfire regrowth and biomass accumulation may exacerbate the risk of more frequent fires.

We neglect the occurrence of adverse climatic years accounting for the most severe and catastrophic fires [*Westerling*, 2006] and discuss the resulting fire regime that is interpreted as an intrinsic property of vegetation, climate, and land use. Climate may hinder the interrelation between fuel availability and fire in climate-driven fire regime [*Pausas and Fernandez-Muñoz*, 2012].

Due to the lack of spatial resolution, the model ignores the real-world landscape fragmentation and vegetation pattern connectivity [*Fischer and Lindenmayer*, 2007] which could be accounted for by introducing appropriate parameters into the lumped model equations. We expect these ecosystem traits to add more complexity to the fire dynamics. While fire spreads over progressively more connected areas where enough fuel is available [*Shakesby*, 2011], the land use change produces a patchwork of disconnected and heterogeneous subcatchments, where less fire-prone cultivated areas alternate with abandoned zones. The former acts as a fire barrier, while the latter serves as a limited fuel productivity area where frequent and moderately destructive fires develop and extinguish with a frequency that depends on the extent of the patch. As the number of disconnected abandoned subcatchments increases, the whole catchment fire regime results from the superposition of periodic subcatchment fires with different frequency, amplitude, and phase shift. After the different patches of the mosaic are connected to each other and large portions of the catchment are reforested, the fuel-driven fire regime is expected to switch toward a chaotic, low frequency, but extremely destructive, fire regime that certainly deserves attention, survey, and a combative strategy.

The area burned by fuel-driven fire increases with land abandonment (according to the experimental evidence [*Pausas and Fernandez-Muñoz*, 2012]), but the fire frequency decreases contextually (conflicting with the experimental evidence [*Pausas and Fernandez-Muñoz*, 2012]), suggesting a change of fire drivers, overwhelming the importance of fuel availability.

Criticality, defined as the state of development of fires of any magnitude following (lightning or human) ignition, has been found close to forest closure according to several previous models [*Casagrandi and Rinaldi*, 1999; *Malamud et al.*, 1998, 2005]. The average forest biomass is much closer to its no-fire steady state solution when fire is chaotic than when the fire regime is periodic (at intermediate stages of land development). Therefore, the TPTP approach suggests that it could be a property of the ecosystem self-regulating the biomass and fuel production and vanishing as the land use activity changes.

In the chaotic fire regime, typical of the Mediterranean ecosystem, easy-to-handle power law relations have been proposed to estimate the risk of fire [*Malamud et al.*, 1998, 2005], although fire control is complicated by the lack of predictability of each fire event and its magnitude. Fire management in Mediterranean forests has mostly targeted fire suppression rather than fire prevention, even though suppression of small medium-intensity fires is often successful, unlike that of large high-intensity fires [*Raftoyannis et al.*, 2014]. When fire is cyclic, it is also more predictable, and this could provide opportunities for successful fire control strategies based on fuel control. In switching from fuel- to weather-dominated fire regimes, climate indicators should be identified for effective fire control [*Barros and Pereira*, 2014].

5. Conclusion

We presented a new model for wildfire dynamics that demonstrates the impact of land use change on forest fire regime and predicts the sequence of three different fire regimes along a land development gradient: no-fire, cyclic fire of increasing complexity, and chaos. Starting from a no-fire regime when all the land is almost completely cultivated, the ecosystem reaches a chaotic fire regime passing through intermediate land development stages, each of which has limit cycle fire dynamics. As cropland abandonment progresses, the model predicts a sudden increase in fire frequency followed by a progressive reduction in fire frequencies and an increase in fire intensity (as the fuel load increases). Wildfires exhibit a robust regime sequence along the land development gradient in three different aridity scenarios.

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