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Forest fire management to avoid unintended consequences: A case study of Portugal using system dynamics

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ABSTRACT

Forest fires are a serious management challenge in many regions, complicating the appropriate allocation to suppression and prevention efforts. Using a System Dynamics (SD) model, this paper explores how interactions between physical and political systems in forest fire management impact the effectiveness of different allocations. A core issue is that apparently sound management can have unintended consequences. An instinctive management response to periods of worsening fire severity is to increase fire suppression capacity, an approach with immediate appeal as it directly treats the symptom of devastating fires and appeases the public. However, the SD analysis indicates that a policy emphasizing suppression can degrade the long-run effectiveness of forest fire management. By crowding out efforts to preventative fuel removal, it exacerbates fuel loads and leads to greater fires, which further balloon suppression budgets. The business management literature refers to this problem as the *firefighting trap*, wherein focus on fixing problems diverts attention from preventing them, and thus leads to inferior outcomes. The paper illustrates these phenomena through a case study of Portugal, showing that a balanced approach to suppression and prevention efforts can mitigate the self-reinforcing consequences of this trap, and better manage long-term fire damages. These insights can help policymakers and fire managers better appreciate the interconnected systems in which their authorities reside and the dynamics that may undermine seemingly rational management decisions.

1. Introduction

This paper explores how dynamical interactions between the physical and political systems of forest fire management influence allocation of resources to the reactive suppression of fires and their proactive prevention. Portugal is the model case.

1.1. Motivation

Demographic, agricultural and climatic changes are altering the dimensions of forest fire management in many regions. Vast populations are moving from the countryside to urban areas. This depopulation of marginal agricultural areas leads to extensive afforestation, through either second growth woodlands that invade previously tended fields or deliberate shifts to forest plantations (Pereira et al., 2006; Vallejo, 2005). Climate change also appears to be influencing patterns of rainfall and weather that can exacerbate fire damages, as witnessed in 2012 in the Western United States. Together, these changes increase forested area, the potential damage from forest fires, and thus the importance of informed expenditures on fire management.

Portugal is grappling with the consequences of these changes (Fig. 1). The number of forest ignitions increased by nearly a factor of ten between 1980 and 2010, from about 4000 to as many as 35,000 annually. The decadal average of burned area in that time period increased from approximately 73,000 to 102,000 to 152,000 ha (AFN, 2010). The years 2003 and 2005 together registered over 750,000 ha burned, that is, about 3000 square miles – an area of more than 50 miles on each side and almost 9% of the entire country. These damages motivated great attention to forest and fire management and led to significant expenditures on the country's capacity to suppress fires (Beighley and Hyde, 2009; Beighley and Quesinberry, 2004; Oliveira, 2005). Much of the recent research

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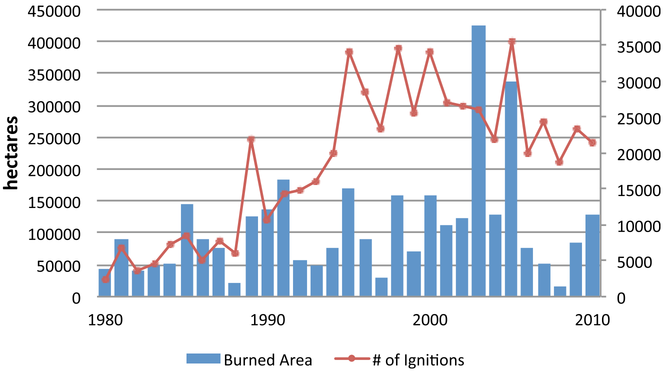

Fig. 1. Total burned area and ignitions in Portugal, 1980–2010 (AFN, 2010). Both are increasing and becoming increasingly volatile.

has sought to explain the growing fire occurrences statistically using a variety of physical and socioeconomic variables (Catry et al., 2010; Marques et al., 2011; Moreira et al., 2009).

There are, however, underlying dynamics that have been impacting fire activity in Portugal for many years. Specifically, the country has witnessed the afforestation of pine on public lands (Brouwer, 1993), extensive commercial investments in eucalyptus plantations (Mendes et al., 2004), and thus a great increase in the total area of contiguous, fire-prone forest. Meanwhile, rural abandonment of farming and emigration into the coastal cities after the 1960s (DGRF, 2006; Gomes, 2006; Moreira et al., 2001), reinforced by European Union policies (Aguilar and Montiel, 2011), changed the susceptibility of the landscape to forest fires. Traditional farming practice had kept fuel levels reasonably stable through integrated agriculture, livestock grazing, and fuel management; however, as farms were abandoned, tall shrub lands and mixed forests began to dominate the landscape resulting in a 20–40% increase in fuel accumulation (Moreira et al., 2001). Increased fuel loads can increase the rate of fire spread, intensity and, all things equal, fire severity (Graham et al., 2004; Peterson et al., 2003; Weatherspoon and Skinner, 1996). This is particularly true in the northwestern Iberian Peninsula (Northern Portugal, Asturias and Galicia) due to high plant productivity (Vázquez et al., 2002). Despite these facts, Portuguese management strategy has generally promoted the exclusion of fire, as has been the case in other Mediterranean countries like Greece, Spain and Italy (Morehouse et al., 2011; Secco et al., 2010; Seijo and Gray, 2012). For further reading on Portuguese fire history, the reader should consult Grove and Rackman (2003) and Pereira (2006).

Effective management of the risk of forest fire balances suppression and prevention activities. As defined in this paper suppression seeks to extinguish fires already ignited, while prevention seeks to limit fire severity through fuel reduction, for example through prescribed fire. In Portugal, forest managers have used prescribed fire since the 1970s to mimic historical fire regimes (Silva, 1997), reflecting their knowledge of the ecosystem's dependence on fire for vitality and renewal. However, suppression expenditures have come to dominate the budget since the major fires in the mid-2000s (ISA, 2005). While fire (whether natural or prescribed) is often essential to the overall health of the forest ecosystem, the ecological benefits of fire are outside the scope of this study. Thus, when discussing forest fire management henceforth, the focus is on managing fire damages to protect people and property. Nonetheless, striking an appropriate balance between suppression and prevention efforts is a non-trivial policy goal, particularly when one action can potentially undermine another through complex and sociopolitical feedback effects.

1.2. Research approach

An essential premise of this paper is that a better understanding of the dynamical interactions between components of the forest fire management system can improve managerial prescriptions. Systems thinking is a general approach for developing this understanding. It trades losses in contextual detail of any one component of the system for subsequent gains in understanding of phenomena that emerge due to component interactions and feedback.

System Dynamics (SD) is a quantitative modeling tool that uses systems thinking to analyze the impact of feedback loops in complex, dynamic systems. This paper uses SD to model and then simulate the dynamics of a forest fire management system, focusing on the interactions between the physical aspects of forest fires and the political responses to fires over time. It provides a comparison between reactive and proactive policies: between immediate responses that target symptoms (suppression) and longer-term actions that address underlying causes (prevention). Finally, it explores the ways in which physical and political dynamics interact and may lead to unintended and unexpected consequences. It is a specific application of a general approach that has been applied in many other contexts.

The analysis runs over decades. This is the necessary, appropriate time scale for exploring the dynamic feedback effects of alternative strategic policies. This approach therefore differs from those that focus on short-run, static decisions concerning optimal allocation of firefighting resources.

The following two sections describe the modeling approach in more detail, and then apply it to forest fire management in Portugal. The subsequent two sections assemble the simulation and present results in light of the particular dynamics in Portugal.

2. Systems Dynamics modeling

Broadly speaking, Systems Dynamics (SD) is a modeling approach and simulation tool for modeling complex, dynamic systems. SD captures an essential feature of many systems: that they are self-regulating over time. This means that feedbacks among the system components incrementally adjust the state of the system. A change in one part of the system affects another that then affects others with some delay, some of which will eventually feedback to amplify or dampen the effect of the original change. In short, an SD model recognizes that changes do not occur in isolation and furthermore that many systems do not respond instantaneously to these changes.

Self-regulating systems are endemic in nature and society. They are particularly apparent in complex ecological and social systems, as well as systems that accumulate quantities, or stocks, of variables that are central to system function. A forest is a good example: fire sets off a cycle of regrowth, which leads to increased fuel loads over time and thus a greater propensity for fire. Similarly, bureaucratic changes take time to respond to new situations such that any subsequent equilibrium takes time to establish. For this reason, SD is a suitable approach to explore the interconnected and dynamic issues of forest fire management.

SD represents the interactions between the elements of the system through causal loops. For example, a year with particularly damaging fires may incite the government to increase the budget for firefighting. This leads to more firefighting equipment and personnel, reducing the damage that might arise from fires several years following the year that triggered the initial change. Such feedbacks with delays and influences from other system variables can produce nonlinear and unexpected behavior, such as self-reinforcing positive feedback. In general, feedback can lead to unintended consequences of seemingly rational policy decisions (Sterman, 2000).

SD is a well-established and valid approach for analyzing the management of complex environmental systems. Examples include water resource management (Simonovic, 2002; Stave, 2003), agricultural development (Saysel et al., 2002) and global climate change (Sterman, 2011).

SD takes a holistic approach to analyze the impacts of complex dynamic interactions in a system. It captures the effects of feedbacks so that policies can be evaluated in light of their systemic ripple effects. SD represents systems by connecting each individual causal loop into an integrated causal loop diagram. These high-level diagrams usefully represent the overall feedback structures of complex, self-regulating systems.

2.1. *Forest fire management model*

Fig. 2 is a causal loop diagram that represents the high-level dynamics impacting a forest fire management system. The left-hand box represents the physical subsystem, how forest growth increases fuel load, fire severity and burned area. The right-hand box represents the political subsystem, showing the influence of human decision-making on forest fire management. While economic, socio-ecological, and other subsystems could be included in the model, the physical-political scope is sufficient for the aims of the paper. Variables within boxes are the stocks that define the state of the system at a given time.

An SD model simulates system performance over time by appropriately altering the variables. For each increment of time it adjusts the level of each variable as determined by the net inflows and outflows. For example, the growth of the forest over the previous year increases fuel load, but the forest burning that occurs during the current year subsequently decreases fuel load.

Both the physical and political systems contain feedback loops. Within the physical system, the natural balancing loop is the *Native Fire Regime*. It represents the fact that fuel accumulates according to some growth rate; that as fuel load increases, so too does fire severity; this then increases burned area per year and subsequently drains the fuel stock through burning. It represents basic ecosystem dynamics of a forest undisturbed by human influence.

Within the political system there are two feedback loops. The balancing *Fire Control* loop depicts how an institution, or set of institutions, attempts to manage the frequency and severity of fires through enhanced fire suppression. Thus, as burned area per year increases, there is more pressure to control fire in order to protect people, property and industry. This leads to more suppression expenditures and subsequently shorter fire durations as crews can extinguish fires faster and more effectively with enhanced suppression technologies. With shorter fire durations, burned area per year decreases, representing the balancing effect.

The second political cycle is the reinforcing *Prevention Resource Scarcity* loop. Assuming a finite budget, increased suppression expenditures crowd out the resources available to prevention activities, such as prescribed fire. This in turn decreases the preventative removal of forest fuel, and the fuel stock increases, as Saveland (1998) indicated. Some authors contend that excess fuel accumulation is a direct consequence of fire exclusion, since small and medium fires are not allowed to burn (Minnich, 1983, 2001;

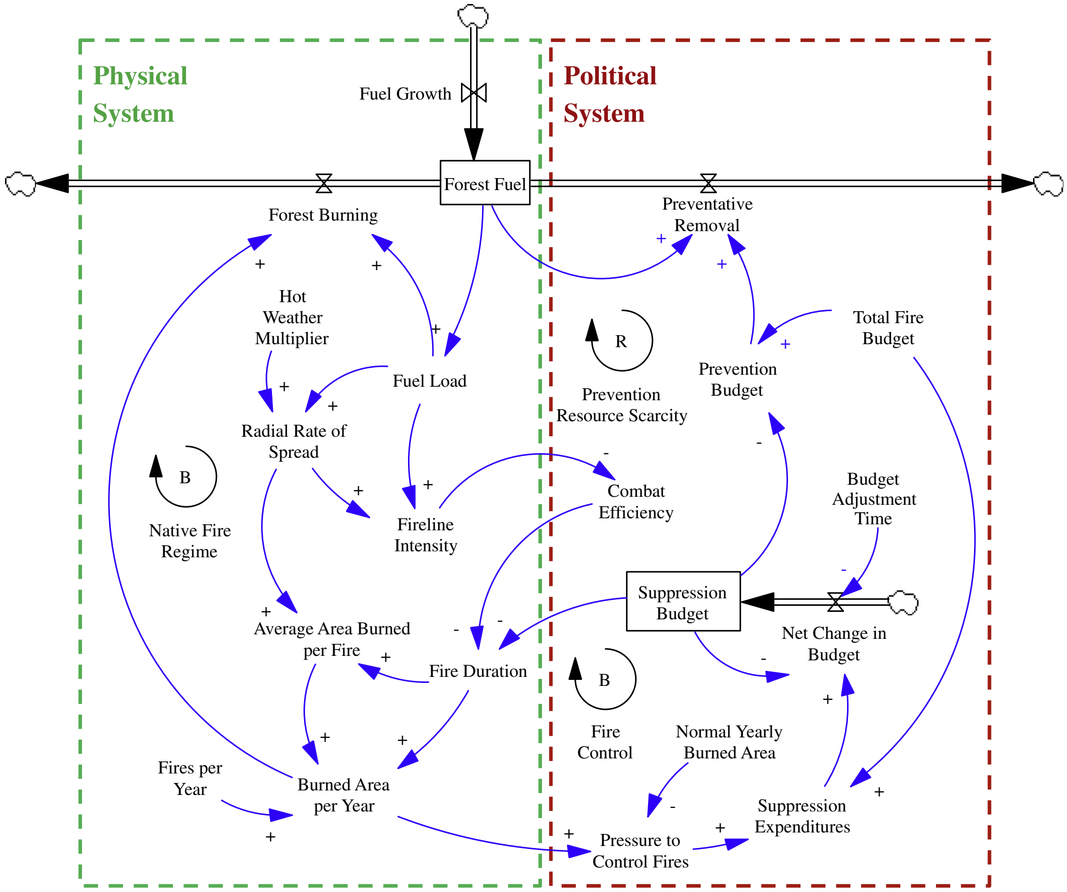

Fig. 2. Causal loop diagram of a forest fire management system. The diagram distills the complexity of the system into the major variables and feedback loops ('B' stands for "balancing" and 'R' for "reinforcing") between physical and political subsystems.

Minnich and Chou, 1997). While others dispute the basis for this dynamic (Keeley and Fotheringham, 2001; Keeley et al., 1999; Moritz et al., 2004), and it is likely to depend on the local vegetation structure, this feedback loop is important for appreciating the potential unintended consequences of decisions about managing forest fires.

2.2. The physical system

The complete forest fire management model involves significant detail for both the physical and political system. Supplementary material associated with this paper and Collins (2012) provide full particulars. This and the next section indicate salient elements of these details.

Fuel Load is the key variable that links fire suppression and prevention activities to eventual fires. Its units are metric tons per hectare, consistent with the measurements conducted for experimental burns in Portugal (Fernandes, 2001; Fernandes et al., 2009).

The *Radial Rate of Spread* of fires is roughly proportional to the square root of fuel load, as in Fernandes et al. (2009). The *Hot Weather Multiplier*, which has a multiplicative effect on fire spread, is an annual index of weather conditions represented by the average dryness of fuel in a given fire season (year). It is a white noise process that generates truncated normally distributed random variables to reflect the occurrence of hot, dry weather particularly conducive to major fires, as done in Li et al. (1997). The model represents aggregate fire activity and thus all variables, including the weather multiplier, are aggregate measures taken over the entire year.

The *Fireline Intensity* is the rate of heat energy released per unit time per unit length of fire front (Byram, 1959). It reflects the associated reduction in firefighting *Combat Efficiency*. For example, direct attack with hand tools and assured control of prescribed fire is possible when intensity is less than 400–425 kW/m. Heavy mechanical equipment can usually control a fire if intensity is below 1700–1750 kW/m. Spot fires can become serious at 2000–2100 kW/m, and fires are completely uncontrollable when intensity exceeds 3500–3700 kW/m (Chandler et al., 1983; Hodgson, 1968).

Burned Area per Year is calculated as the product of *Fires per Year* and *Average Area Burned per Fire*. The product of this value with *Fuel Load* determines the amount of *Forest Burning* that occurs each year.

The analysis focuses on yearly aggregate impacts. It ignores the distribution of individual fire durations and uses averages. Every fire in the model behaves in the same way; it has the same fireline intensity, radial rate of spread, and duration. However, the model does represent single extreme fire seasons, which ultimately are the impetus for subsequent government action. This is sufficient for modeling the high-level dynamics between humans and the forest.

2.3. The political system

Pressure to Control Fires is a dimensionless variable that encapsulates management action taken given fire damage from the previous year. It is defined as the quotient of *Burned Area per Year* and *Normal Yearly Burned Area*, and relates to the expenditure on suppression resources. This accords with the views of many Portuguese experts from academia, industry, and forest owners' associations who contend that forest management expenditures are driven largely by politics. In other words, pressure from the media and the public result in expenditures on high-tech firefighting solutions, such as helicopters and air tankers, because they resonate emotionally and psychologically with public opinion.

A first order information delay modulates the budgeting for suppression expenditures. This is essentially a smoothing function. When expenditures change in response to last year's fire season, they are compared against the current budget and altered according to the adjustment time required to pass new budgets, which is assumed to be three years. The rationale behind using this structure is that the budget adjustment process can be slow, which dampens the budgetary impact of a particularly bad fire season. Such delays are widely used in stock and commodity forecasting to filter out short-term fluctuations in prices (Sterman, 2000).

A higher *Suppression Budget* increases firefighting capability, drives down *Fire Duration*, and decreases forest burning. This is the balancing mechanism of the *Fire Control* loop from Figure. The effect of more suppression resources is to decrease fire duration at a decreasing rate, in accord with the LCD model (Sparhawk, 1925). Martell (2001) proposes the same effect although through a different mechanism. *Combat Efficiency* reflects the effectiveness of a given *Suppression Budget* at decreasing *Fire Duration*.

The *Total Fire Budget* is the annual sum of resources allocated to suppression and prevention. Assuming finite budgets, increases in suppression expenditures decrease the resources devoted to prevention and fuel removal (e.g. via prescribed burns). Given the historical tendency of governments to favor fire exclusion (Aguilar and Montiel, 2011; Franklin and Agee, 2003), there is thus a tendency to crowd out prevention activities.

3. Model adaptation to Portugal

To explore the implications of suppression- and prevention-based policies for fire management, we adapted the model to the past and current situation in Portugal and implemented it in the Vensim software package. It should be emphasized that the purpose of the model is to evaluate the aggregate dynamics of factors affecting the forest fire management system under alternative management scenarios, i.e. different allocations to suppression and prevention resources. It is *not* to reproduce historical fire regimes in Portugal.

To establish an adequate long-term view, the model covers three periods of forest fire management. The first is the past period of intense rural inhabitation and agriculture. The second represents the transition associated with the political and economic opening to continental Europe. This was a period of rural depopulation, extension of forest plantations, and shifts in forest management practices. The third phase is that of eventual stabilization after the transition. To permit adequate steady-state conditions before and after the transition period of about 50 years, we gave all periods equal length. Thus we set up the model to run for 150 years. For convenience, one can assume that the 150-year span begins in 1900 and runs until 2050. The simulation time step is one year, corresponding to the annual cycle of fire seasons and budgets.

Total Forested Area was set to an upper-bound estimate of the current coverage of forest and shrubland in Portugal, approximately 5.4 million hectares (Oliveira, 2011). *Fires per Year* were assumed constant at the prevailing 10-year average in Portugal, or 24,528 occurrences. The *Total Fire Budget* was set at the approximate 2009–2010 level of €150 million. The model increases *Fuel Growth* 1% per year in the transition period, from years 50–100. This exogenous ramp is an approximate portrayal of the afforestation and rural abandonment that started around the 1950s in Portugal. At the end of this phase, the model assumes that fuel growth rate stabilizes at a level roughly 50% greater than where it started.

The model is parameterized such that the system begins in equilibrium (before the onset of afforestation and rural abandon), with yearly burned area equal to the 10-year average in Portugal, approximately 150 thousand hectares. The notion of equilibrium in a forest ecosystem, let alone any system influenced by humans, may be a bit contrived. With high variance in yearly ignitions, physically diverse regions, and general uncertainty surrounding human action, the forest system is almost constantly in flux. However, to identify the impact of relevant dynamics on the system, a baseline mode must be formulated from which to compare the results of various disequilibrium simulations. Development of the equilibrium operating mode (essentially where fuel into the system equals fuel out of the system) requires assumptions and should of course be subject to scrutiny. However, the initialization of equilibrium is less significant, since it is the *divergences* from equilibrium due both to afforestation and rural abandon and physical-political dynamics that are central to the analysis.

4. Assembling the baseline analysis

To explore and illustrate relevant dynamics and tradeoffs in fire management, we first examine the consequences of two divergent policies, one focused on suppression, the other on prevention (the chosen percentages produce outputs that depict well the effect of feedback on the system). The results characterize the impacts of these policies and help develop the understanding of the counter-intuitive effects of seemingly rational policies.

The two baseline policies are nominally defined as:

- *Suppression Policy*, which devotes 60% of initial resources to suppression, and
- *Prevention Policy*, which devotes 75% of initial resources to prevention.

These allocations of resources cannot be altered exogenously at later stages in the simulation. While this capability could be implemented, disallowing it in the current structure isolates the effect of the self-regulating behavior on the system, revealing potential future outcomes of different policies left unchecked. To implement the allocation of resources, the user inputs a fraction (between 0 and 1) of resources to prevention at the beginning of each simulation. With the exception of the allocation, all simulations are run under the exact same conditions.

Following the exploration of these two alternatives, we explore the possible effects of alternative policies. Results indicate the possibility of improving the overall performance of fire management through a balanced approach to suppression and prevention.

5. Results of baseline analysis

This section presents the salient outcomes of the two baseline policies. Following the three major feedback loops of Fig. 2, it tracks key output variables over time. Overall, the *Prevention Policy* produces less total burned area in the long run. The *Suppression Policy* confers short-term benefits in terms of shorter fire durations and less burned area. However, it produces overwhelming, self-reinforcing feedback effects after the onset of afforestation and rural abandon that lead to increasingly severe and volatile fire seasons.

5.1. *Fire Control loop*

Under the *Suppression Policy*, the suppression budget eventually approaches the total budget. As fuel loads increase, fires become more intense, prompting more efforts on suppression, thus less on prevention and its reduction of fuel loads. This propels full-scale efforts to suppression.

A focus on fire suppression results in shorter fire durations (Fig. 3) and therefore less burned area per year, which is the goal of fire suppression. This is the *intended* consequence of increased fire suppression and the *Fire Control* loop in general.

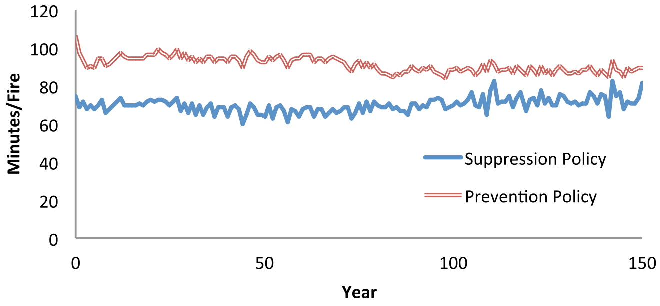

Fig. 3. Fire Duration. Fire durations (minutes/fire) are shorter under the *Suppression Policy*, which is the intended effect of the policy.

5.2. *Prevention Resource Scarcity loop*

Suppression Policy produces *unintended* consequences that become evident when we consider the *Prevention Resource Scarcity* loop. It is associated with increases in the rate of spread of each fire and dramatic increases in relative fireline intensity. Intense fires reduce the combat efficiency of fire suppression forces, decreases their ability to manage fires effectively, which in turn leads to longer fires. If not for the increases in intensity, the fire durations under fire exclusion would be shorter than shown in Fig. 3. In short, emphasis on suppressing fires can make them more severe.

The primary physical reason for the *unintended* consequences is that the *Suppression Policy* leads to an excessive accumulation of fuel, caused by its associated lack of investment in preventative fuel removal (Fig. 4).

The underlying political reason for this is that the *Suppression Policy* concentrates effort and resources on suppression, and thus drives down the budgets for prevention. As preventative fuel removal decreases, the stock of fuel increases, which leads to increases in fireline intensity (and associated decreases to combat

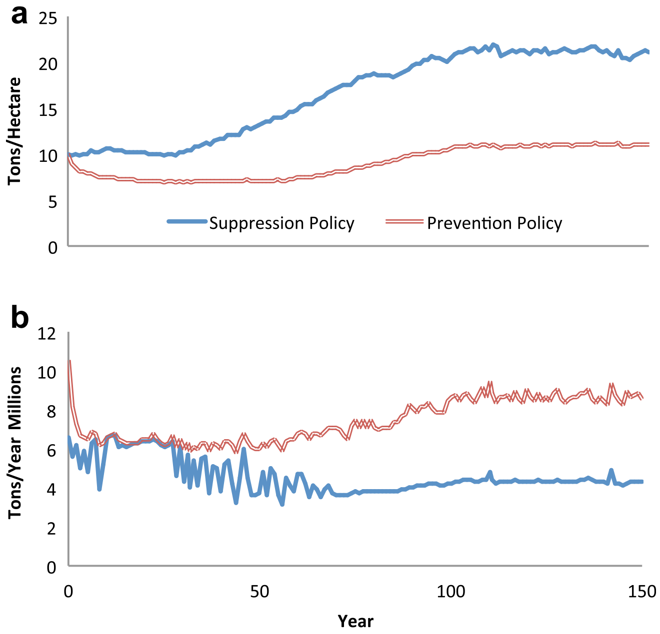

Fig. 4. a: Fuel Load. The *Suppression Policy* is associated with greater growth in fuel load (tons/hectare) compared to the *Prevention Policy*, which is the unintended effect of the policy. b: Preventative Removal. With a finite budget, excessive suppression expenditure under the *Suppression Policy* crowds out preventative removal. As the rate of preventative removal (tons of fuel per year) decreases, fuel load increases.

efficiency) and rate of spread. The combination of these factors translates to more burned area and further pressure to manage fires with additional suppression forces. Thus, increased suppression expenditure reinforces further expenditure, and the *Fire Control* loop has an *unintended* positive effect on the fuel stock.

5.3. Native Fire Regime loop

Examination of the native fire regime loop further reveals the *unintended* consequences of a focus on fire suppression. This loop recognizes that forest fires combine with preventative fires to reduce fuel loads. Since the *Suppression Policy* greatly increases the annual forest burning over time (Fig. 5), one might expect that the reduction greatly reduce the total fuel load. However, this is not the case (Fig. 4a). This means that the balancing effect of the *Native Fire Regime* loop is being overwhelmed by the lack of preventative removal stemming from the *Prevention Resource Scarcity* loop, which itself is driven by the unintended consequences of the *Fire Control* loop set into motion by afforestation and rural abandon.

5.4. Overall result

The overall result is that a focus on fire suppression provides immediate benefits but can become an inferior policy over time. The *Suppression Policy* leads to smaller burned area at first, but after the onset of afforestation and rural abandon, burned area per year surpasses that associated with the *Prevention Policy* and becomes more volatile (Fig. 6a). Correspondingly, the *Suppression Policy* leads to eventual greater total burned area (Fig. 6b).

An important goal of fire management policy is to manage total costs, for which the metric of total burned area is a proxy. From the perspective of this measure, *Suppression Policy* is the better policy initially through the transition period of rural abandonment and afforestation, that is, until approximately year 100. However, at some point during the transition period the reinforcing loops that increase burned area overcome the balancing loops seeking to decrease it, resulting in an increase in the rate at which the area burns. Because burned area continues to increase under the *Suppression Policy*, suppression expenditure remains at near maximum, perpetually undermining preventative fuel removal and thus keeping fuel loads high, which in the model is the underlying cause of severe fire activity. Overall, the *Suppression Policy* has the *unintended* consequence of increasing total fire damage.

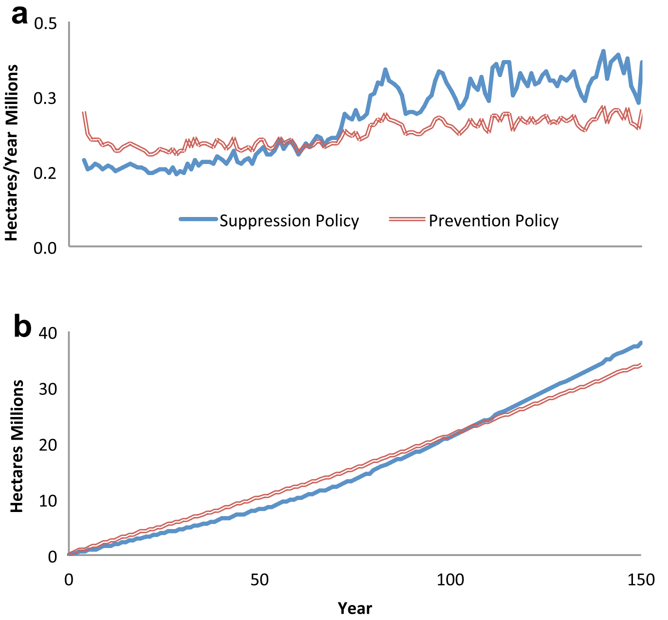

Fig. 6. a: Burned Area per Year, 5-year moving average. The *Suppression Policy* results in annual burned areas (hectares/year) that are mild at first, but in the long run become increasingly severe and volatile. b: Total Burned Area. The *Suppression Policy* results in total burned area (hectares) that is initially smaller but eventually larger than the *Prevention Policy*, revealing its long-term inferiority.

6. Discussion of results

The results show how the reflex to fix a problem can, counter-intuitively, make matters worse. In the business management literature, this phenomenon is known as the *firefighting trap*, where “putting out fires” is understood allegorically. This section discusses the trap and the related concept of policy resistance, and then offers solutions in the context of actual fire management.

6.1. Firefighting trap

Systems often get trapped in cycles of self-reinforcing feedback whereby the problem symptoms continue to grow yet the solution remains the same. Businesses often refer to this management syndrome as *firefighting*, defined as the short-term fixing of problems, or suppression of their symptoms, rather than understanding and addressing the underlying factors that cause the problems. System Dynamics has been used to analyze this problem in a number of different contexts outside of forest fire management (Godlewski et al., 2011; Repenning, 2001; Sterman, 2000). Absent external intervention or leadership, system managers continue to allocate resources to short-term fixing of symptoms instead of dealing with the causes of problems.

The model indicates that, to some extent, this is what is happening in Portugal. There is continuing emphasis on expenditures and efforts to suppress fires and address recent fire damages. Public pressure following a noticeably intense fire season begins a self-reinforcing feedback loop where preventative fuel removal is

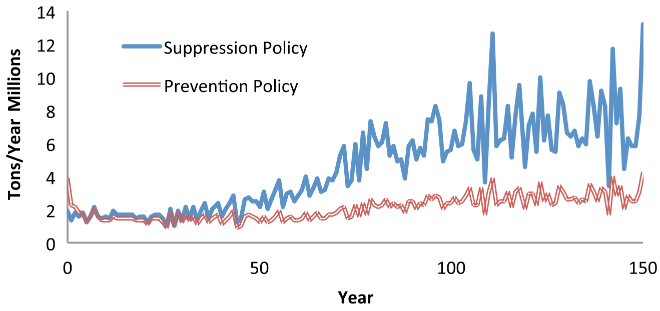

Fig. 5. Forest Burning. The rate of forest burning (tons of fuel per year) becomes larger and more volatile under the *Suppression Policy*.

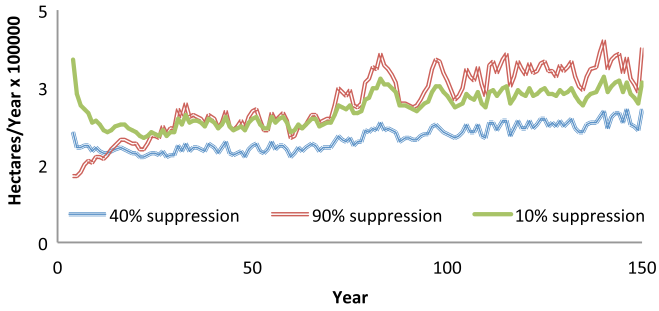

Fig. 7. Burned Area per Year, 5-year moving average. The appropriate balance of suppression and prevention efforts can greatly reduce yearly and total burned area.

diminished and fuel accumulates. More fuel in the system leads to more intense fires, more burned area, and thus further expenditures on suppression.

6.2. *Policy resistance*

The concept of *policy resistance* reflects the reality that interactions within a system may resist and undermine apparently rational management decisions (Sterman, 2000, 2006). A policy to deal with an issue may seem logical or rational, but has unintended consequences that actually exacerbate the problem. A major function of SD models is to illuminate the side effects or unintended consequences of seemingly rational decisions or policies, to expose the sources of policy resistance, and thus to point the way to deal effectively with an issue.

In the case of managing fires in Portugal, decision makers have expanded the suppression capacity of the country in an effort to reduce the frequency and severity of fires. However, the system shows resistance to this policy due to the unintended, positive effect on fuel load. In general, policy resistance is a precursor to self-reinforcing feedback effects and firefighting traps. Yet, despite the resistance of systems to seemingly rational policies, managers often adhere to them anyway due to entrenched mental models of how the system works and institutional or social pressures.

6.3. *Balanced solutions*

Preventing or mitigating the firefighting trap is possible if we allocate sufficient resources to prevention. However, if this allocation is too high, and thus the allocation to suppression too low, then the overall results are also poor.

To illustrate the merit of a balanced policy, we examine three allocations of resources to suppression: 90%, 40%, and 10% (the complements dedicated to prevention). The results show that disproportionate expenditures on either suppression or prevention have adverse long-term consequences (Fig. 7). While great emphasis on suppression can be counter-productive, an insufficient amount is also detrimental as fires burn longer and cause greater loss of property and life. As Fig. 7 indicates, policymakers and fire managers should pursue a balanced approach to suppression and prevention activities. The exact allocation is not meaningful, as the SD model does not seek numerical accuracy. Nonetheless, the realistic result, justified in light of the physical-political dynamics impacting fire management over time, is that a balance of suppression and prevention minimizes total burned area.

While the balanced "solution" to the firefighting trap is straightforward, shifting to this policy involves an important real-world tradeoff in forest fire management that may be difficult to achieve for three reasons:

1. A new emphasis on prevention (and away from suppression) allocates resources to different organizations using different forms of equipment. The established firefighting organizations are likely to contest this policy.
2. Investments in preventative fuel management lack immediate, visible short-term benefits, making them less attractive to both the public and policymakers with short terms of governance.
3. Managers and decision makers rarely receive credit for fixing or preventing problems that never occur (Repenning and Sterman, 2002). Moreover, they simply *cannot* receive credit since the prevention of the problem can never be attributed, with absolute certainty, to their preventative actions.

These obstacles, coupled with the physical-political feedback effects, help illustrate why a balanced approach to forest fire management practice is neither universal nor standard despite the well-accepted tenet that strict adherence to fire suppression may ultimately lead to more severe fires. For example, within and across the US, Canada and Europe, authorities differ significantly in their approach to forest fire management (GAO, 2007; Hirsch and Fuglem, 2006; Montiel and Kraus, 2010), though there is evidence that the US is reversing its long history of fire exclusion (Reynolds et al., 2009). In contrast, preventative measures like prescribed burning are a well-accepted pillar of fire management in Australia; the debate instead centers on the appropriate amount to conserve biodiversity (Penman et al., 2011).

As regards Portugal, the SD model illustrates the tradeoffs between fire suppression and preventative fuel removal to inform balanced policy. Afforestation and rural abandon starting in the middle of the 20th century steadily increased fuel loads across Portugal, which led at least in part to the increase in fire activity over the past several decades. The symptomatic solution was to increase fire suppression capability in order to limit the damage of forest fires. Such a policy is immediately attractive: the public lauds decision makers for swiftly addressing the forest fire problem, and appreciates the decrease in fire durations across the country. However, a focus on fire suppression may not be sustainable in the long run, as the combination of high fuel load and severe weather can overwhelm the suppression capacity of Portugal, as was the case in 2003 and 2005 (Fig. 1). These model-assisted findings may help Portugal shift its current policy toward the more balanced approach that Australia has adopted.

6.4. *Model limitations*

This paper uses a System Dynamics model to derive insights about the unintended consequences of seemingly rational policies that arise due to system feedback. The general causality governing the model is consistent with the literature and the testimonies of Portuguese fire experts. But, SD models do not provide statistically valid estimates; rarely are they more than 40% accurate (Chahal and Eldabi, 2008). They provide a demonstration of the unintended consequences of certain actions that arise due to self-regulating feedbacks in the system. While the graphical outputs presented have absolute numerical axes, the numbers should not be taken at face value.

It is important to note that the shape of the model trends are sensitive to the monotonic functions in the model linking variables for which a physical equation or significant statistical relationship does not exist. The sign of all these relationships (i.e. positive or negative) is logical, but their exact shapes (i.e. range, domain, curvature) are either based on anecdotal evidence from experts or an informed guess by the research team. Further discourse with various experts and additional fieldwork could establish more reliable and data-driven functions.

While SD is useful for gaining overall insights into complex system behavior, one of its shortcomings is that it is a simulation tool based on deterministic causal processes. While some systems, such as manufacturing plants and assembly lines, are characterized by repeated actions, the reality is that most systems, and certainly forest fire management, are subject to great uncertainty. A lot of this uncertainty stems from the fact that humans constantly interact with systems in attempts to change them. As a result, a deterministic simulation model of a system, based on timeless relationships between political/social and physical/technical factors, never fully represents a system over time.

This limitation is particularly evident in the model of this paper. An initial allocation to suppression and prevention resources runs its course in the feedbacks of the system for 150 years. Due to the structure of the self-regulating feedbacks, it is never possible for the system to increase the resources dedicated to prevention. They only change based on how suppression resources changed following a given fire year. Thus, after a severe fire year, the system will *always* invest heavily in suppression for the upcoming year, whereas investing heavily in fuel management is also a perfectly legitimate (and some might judge better) budget decision. To suggest that political decision makers will always spike suppression expenditures after an extreme fire season is to ignore the human ability to learn from the past and adapt decision making accordingly.

Finally, it is worth noting again that this paper does not consider the ecological benefit of fire when assessing the merits of different policies. While a balanced policy, as defined above, would appear to minimize total burned area, achieving this objective may be at odds with the broader forest management objectives of ecosystem stability and biodiversity conservation. The non-economic, ecological benefits of fire were not modeled explicitly in this paper, but future work focused on adaptive fire management, as opposed to damage control, should include a socio-ecological system in addition the physical and political systems. The expandability of model boundary to include other subsystems is one of the strengths of SD, though any increase in system scope needs to be traded off against potential loss in individual component specificity.

7. Conclusions

This work extends the field of forest fire management by developing a dynamic model that describes major feedbacks affecting system behavior. This broader systems perspective complements the range of available static and narrowly defined optimization studies.

This paper examines the unintended consequences of management decision-making when it focuses on fixing rather than preventing problems, a phenomenon coincidentally known in the business management literature as the firefighting trap. In the case of forest fire management, the finding is that the system succumbs to this trap when political influence increases emphasis on fire suppression and neglects fire prevention. While excessive year-to-year investment in fire suppression may mitigate fire damages in the short-term, in the long-term it can undermine preventative efforts, which becomes increasingly problematic as fuel accumulates. The analysis explored this issue through a case study of Portugal.

The insights from this paper may help policymakers and fire managers better appreciate the interconnected systems in which their authorities reside and the dynamics that may undermine seemingly rational policies. The model contributes to a long-standing debate between the relative merits of suppression versus prevention investments. As a tool, it provides long-term insights for risk communication to the public and exposes policymakers to the non-obvious feedback loops they may face when making management decisions. The results should be applicable to fire-prone countries, particularly those that have relied on policies of fire exclusion, such as Southern Europe and the United States, in addition to Portugal.

Future work could apply costs to different suppression and prevention activities, so that total managerial costs and fire damages of alternative policies can be evaluated. Furthermore, cost-constrained decision-making at later time periods could be implemented in the model instead of only choosing an initial allocation. The user could then use past information on system behavior and update decision making accordingly. Finally, it would be useful to incorporate additional stochasticity into the model, such that decision making would account for uncertainty in the variables currently assumed to be deterministic.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.08.033.

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