Forest Fire Management in Portugal: Developing System Insights through Models of Social and Physical Dynamics

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Abstract

Managing forest fires is a serious national problem in Portugal. Burned area has increased steadily over the past several decades, with particularly devastating years in 2003 and 2005. Ignitions also spike dramatically in summer, which greatly strains firefighting resources and leads to fires that are insufficiently extinguished and later may rekindle. The response of policymakers and fire managers to these problems has largely been to increase fire suppression capacity and technology deployment.

This research asks, what are the side effects or unintended consequences of policies dedicated to large and aggressive suppression forces? Much of the previous work in forest fire management focuses on narrowly-defined, static problems solved using optimization analysis. This research uses dynamic analysis, specifically System Dynamics, to explore how self-regulating feedback loops affect the outcomes of forest fire management decisions over time. Two models are developed. The strategic model explores the dynamic between suppression and prevention expenditure and its effect on long-term burned area. The operational model explores the dynamics through which rekindled fires occur. The results from both models show that interactions between relevant social and physical systems, in the form of public or institutional pressure, can force aggressive suppression decisions into practice. Furthermore, strict adherence to these policies can trap each system in a state of long-run worse behavior due to the overwhelming effects of negative feedback loops. Policy recommendations based on the results, and informed by an in-depth analysis of relevant stakeholders and impediments to implementation, are also presented.

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Acknowledgments

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Having conducted research on a major problem in Portugal, I've had the chance to work with some pretty amazing people from the country. João Claro, my "unofficial" adviser from the University of Porto, is a consistent and reliable source for intellectual discussion on pretty much anything, let alone mathematical modeling and optimization analysis. Carlos (Abílio) Pacheco, my Portuguese counterpart on the FIRE-ENGINE project, works harder than anyone I've ever known; I'm grateful for the numerous get-togethers with his family to which he kindly invited me. Finally, Tiago Oliveira, our energetic and highly motivated liaison/collaborator from grupo Portucel Soporcel, with whom I unfortunately never had the pleasure of surfing with in Matosinhos, is a valued contributor to this work. With all of you I've enjoyed every minute of our personal and professional development together. Obrigadinho.

The Technology and Policy Program (TPP) has been a unique and rewarding experience at MIT. From TPSS, to SPI, to the Energy Club, I've really benefited from taking on extracurricular responsibility in addition to staying on top of classes. I'm happy to have developed relationships with each and every one of my TPP classmates; I'm truly excited to see where everyone ends up in 10 or 20 years. I'm deeply grateful to my TPP adviser, Richard de Neufville, for guiding my development as an effective writer, communicator, policy analyst, and systems thinker. In fact, if I could somehow harness all of those responsibilities into my future vocation in the same way Richard has helped me do so at TPP, I'd be a pretty happy camper. My fingers are crossed.

And of course, I'd like to thank my family for their support along my rather extended academic walkabout, which now may only get longer. Conversations with mom, dad, and my brother Brady have certainly helped put my academic and professional aspirations in perspective. Thanks for keeping me grounded.

As for the thesis, well, it's done.

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Chapter 1. Introduction

Fires are a devilish form of disaster, uniquely difficult to understand and manage compared to other disasters. Unlike floods, earthquakes, hurricanes, or tornadoes, fires can be directly caused by humans. I say directly because the frequency or severity of the aforementioned disasters can be *indirectly* affected by anthropological climate change; however one can simply not start a hurricane in the way that one can start a fire. In addition, while fire can certainly be destructive, it can also serve a rejuvenating role in natural ecosystems. Forest fires consume dead or vulnerable plants such that new and more resilient species can flourish. Thus while we may be interested in preventing, or more realistically mitigating, occurrences of droughts or volcanoes, the same compulsion may not necessarily exist for forest fires. Ultimately forest fires are both a blessing and a curse. Fire was used extensively in early human settlement to alter their environment for beneficial purposes (Pyne, 2001). Native Americans, for example, used fire to cultivate native grasses, modify forest vegetation, and improve hunting (Kimmerer & Lake, 2001; Pyne, 1997). However in the more recent past, forest fires have been exceedingly perceived as threats to human lives and property, resulting in the creation of national and regional forest services, as well as expanding fire suppression capacities across the world. Fire suppression refers to the firefighting tactics, resources, and equipment used to extinguish forest fires. As fire suppression technology has progressed, in general so too have budget expenditures in these technologies.

The culture of the region where fires occur, or the culture of the organization that is commissioned to suppress them will determine *how* the fires are managed. While effective forest fire management is certainly a function of technology, it is inextricably linked to culture as well. This cultural or societal context can be the single most important factor to consider when designing policy. The cultural factors affecting forest fire management in Portugal, for example, are very different from other fire-prone countries in the world.

The practice of forest fire management has evolved considerably in the past century. This evolution has been particularly poignant in the U.S., where fire suppression was the de facto national fire policy of the 20th century (Franklin & Agee, 2003). The U.S. Forest Service has since moved away from this narrowly focused strategy of fire management and embraced a more comprehensive paradigm that stresses *forest* management instead of solely fire management. They recognize the restorative role of fire in natural ecosystems and the consequences of excessive fuel accumulation. Forest fuel is the organic, often very flammable, woody matter that accumulates in forests in between trees. As a result, recent policy has seen an increase in fuel management programs particularly in the pine forests of the Pacific Northwest. Prescribed burning, mechanical thinning, and chemical treatments are preventative tools that reduce fuel loads and/or produce mosaics of treated and untreated areas in order to mitigate the impact of future large fires.

Other countries have managed forest fires without relying on large suppression efforts. In Australia, prescribed burns are part of the fire management culture. They are used to create a mosaic of burned and unburned area in the early part of the dry season to offset the potential area burned by larger, more severe fires in the later part of the season. Indigenous Australians, like Native Americans, used fire to alter their environment in beneficial ways (Pyne, 1991); this cultural relationship with fire may simply have transcended the generations of colonizers in Australia better than it did in the U.S. In Finland, landowners of small forested plots have incentive to keep their forests "clean" (clean here basically means devoid of fuel) and therefore more resilient to fires because they can profitably harvest and sell the wood on the open market.

Admittedly, the climate in Finland is less conducive to severe fire seasons, but the economic incentives currently in place nonetheless motivate landowners to keep their forests protected from fire. The result is less reliance on expensive suppression technologies.

Despite the historical use of prescribed fire among shepherds and farmers in Southern Europe, the policies of most of the countries have been based on total fire exclusion during the past century (Aguilar & Montiel, 2011). Fire exclusion refers to the systematic extinction of all fires on the landscape through fire suppression. Countries such as Spain, Italy, France, and Portugal have been much slower than the U.S. in adopting a more comprehensive management plan, and they have been unable to replicate the economic incentives of Northern Europe. Many of the ignitions in the Mediterranean region are caused by the misuse of fire in rural activities (FAO, 2006), and as a result the use of prescribed fire is largely viewed as dangerous. Despite a mix of centralized (Portugal and France) and decentralized (Spain and Italy) governments, all have had difficulty in passing and implementing regulations on prescribed burning. Part of this difficulty, at least in Portugal, can be attributed to highly fragmented, private forest ownership. On the contrary, in the U.S. most of the forested area is publicly owned, making top-down regulation of the forests easier to implement. Nonetheless, it is worth noting that Portugal has been the first country in Southern Europe to use prescribed burning for fire hazard reduction (Aguilar & Montiel, 2011), though compliance with the rules and enforcement if they’re broken has been limited.

The management of forest fires manifests over a range of time scales, complicated by both social influences (e.g. culture, population density, law enforcement, regional government, influence of private forest owners) and physical factors (e.g. land cover, vegetation types, forest yields, terrain, weather, climate). In addition, the constancy of human-forest interaction and its differing evolution across fire-prone countries, indicate that proper management can only be achieved with increased understanding of the dynamic interplay between relevant social and physical systems.

This research examines forest fire management in Portugal, motivated by FIRE-ENGINE: Flexible Design of Forest Fire Management Systems, a collaboration project with Portuguese academia, industry, and government. In particular, the industry partner is grupo Portucel Soporcel (gPS), one of the largest paper and pulp companies in Portugal. The Engineering Systems Division at MIT was included in the project, among other reasons, to utilize a much-needed systems approach in order to handle the complexity of the forest fire problem in Portugal. To this end, the research uses a combination of semi-structured interviews and System Dynamics modeling. Managing forest fires in Portugal involves a large network of stakeholders, making interviews useful for better understanding the complexity of the problem and also informing the System Dynamics models. The mathematics of System Dynamics are easily applied to physical processes involving stocks and flows (e.g. the growth and burning of forests), as well as social processes with sparse or confidential data (e.g. public pressure to buy new suppression technology). System Dynamics is a continuous-time simulation tool grounded in control theory where the stocks and flows are governed by the presence of feedbacks operating within a system. In other words, a decision made today to alter the current state of the system will impact the state of the system tomorrow, but perhaps in a way not originally intended. Understanding these feedbacks between people and the forest is a central objective of the FIRE-ENGINE project.

The following section details the unique set of physical and socioeconomic conditions in Portugal that have complicated forest fire management over the years. Insights from this research are specific to Portugal, although fire experts from other countries *may* find the content applicable to their respective physical and managerial environments.

1.1 Management Challenges in Portugal

Why are forest fires a major concern in Portugal? For one, the annual economic value of the Portuguese forests is €1.2 million, and their yield in terms of Euros per hectare per year is one of the largest in Europe. The forestry sector represents 3.2% of GDP and 11% of the country's exports through its three main products, pulp and paper, cork, and furniture (Oliveira, 2011a). Therefore, protecting the forests represents an important economic objective, in addition to safety and environmental concerns.

Even though the forestry sector is extremely valuable to Portugal, forest fires are a serious national problem. The number of ignitions, number of hectares burned, and subsequent damages to the ecosystem, property, and the economy have all been increasing (Beighley & Hyde, 2009; Beighley & Quesinberry, 2004; Oliveira, 2005). Figure 1 shows yearly burned area and ignitions in Portugal over the last 30 years. In 2003, fire damages were particularly devastating, burning nearly 450,000 hectares, largely attributable to fires started on just two days in August as well as record synoptic conditions across Portugal (Trigo et al., 2006).

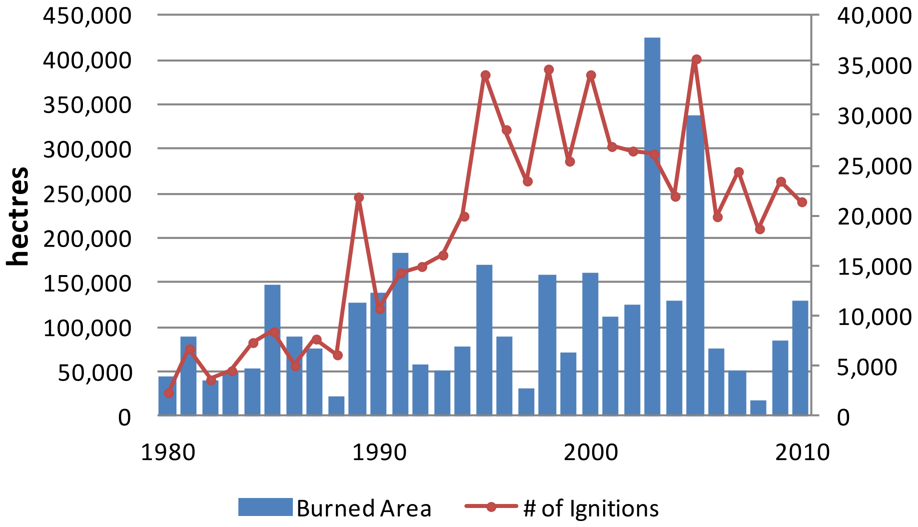


Figure 1. Total burned area and ignitions in Portugal, 1980-2010 (AFN, 2010).

Fires impact the Portuguese forests due to a variety of different factors, some meteorological and some cultural, operating on both long and short time scales. The following two sections separate these factors into those comprising strategic challenges (long-term decision making) and operational challenges (short-term decision making). This distinction, while perhaps a bit contrived, not only distills the systemic fire problem in Portugal, but also guides the modeling effort of scale-compatible social and physical dynamics over time.

1.1.1 Strategic Challenges

Strategic decision making in complex interconnected systems requires long-term vision and understanding of what variables impact the outcome of decisions, and how these outcomes then impact the variables. These endogenous relationships are less visible than external (or exogenous) factors impacting the same variables because their effects may only manifest after a time delay.

In forest fire management, one of these key relationships exists between accumulated forest fuel and fire suppression efforts. Some authors (Minnich, 1983, 2001; Minnich & Chou,

1997) claim that the systematic extinction of all forest fires through fire suppression, i.e. fire exclusion, accumulates excess fuel since small and medium fires are not allowed to burn. This suggests that fuel accumulation is a side effect of fire suppression. Fuel accumulation is a problem because high fuel loads, characteristic of the northwestern Iberian Peninsula due to high plant productivity (Vázquez et al., 2002), are associated with larger, more severe fires (Graham et al., 2004; Peterson et al., 2003; Weatherspoon & Skinner, 1996). Saveland (1998) modeled these relationships with a causal loop diagram (Figure 2), suggesting that not only does fire suppression indirectly accumulate fuel, but that this accumulation also undermines the use of prescribed fire (an ‘s’ on the arrow indicates a “supporting” causal relationship between the variable at the end of the arrow and the one at the front; an ‘o’ indicates an “opposing” relationship). Included around the diagram are quotes from fire managers and forest stakeholders, representing some common assumptions and beliefs. Figure 2 suggests that there is a *tension* between fire suppression and prevention efforts, both related somehow to the accumulation of fuel.

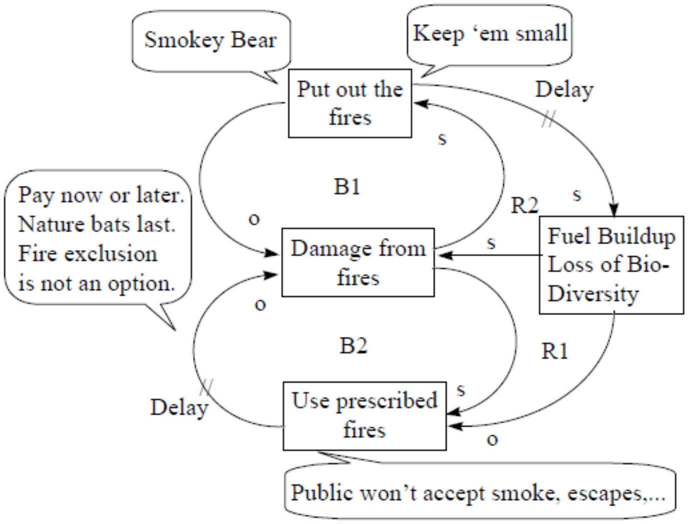


Figure 2. Causal loop diagram of factors impacting long-term forest fire management (Saveland, 1998).

Fuel has accumulated in Portugal over time via other means as well. Afforestation of pine plantations on public lands (Brouwer, 1993) and direct investment in eucalyptus plantations by pulp and paper companies and nonindustrial private land owners (Mendes et al., 2004) greatly increased the total area of forest in Portugal over the course of the 20th century, as depicted in Figure 3. And, with more forested area came more accumulated fuel. Today, rural and forest areas are considerably deserted due to the abandonment of farming activities and emigration flows into the coastal cities, which started to occur sometime in the latter half of the 20th century (DGRF, 2007; Gomes, 2006; Moreira et al., 2001). Traditional farming practice before this time period kept fuel levels reasonably stable through integration of agriculture and livestock grazing with fuel management. However, as farms became abandoned, tall shrublands and mixed forests began to dominate the landscape resulting in a 20-40% increase in fuel accumulation (Moreira et al., 2001).

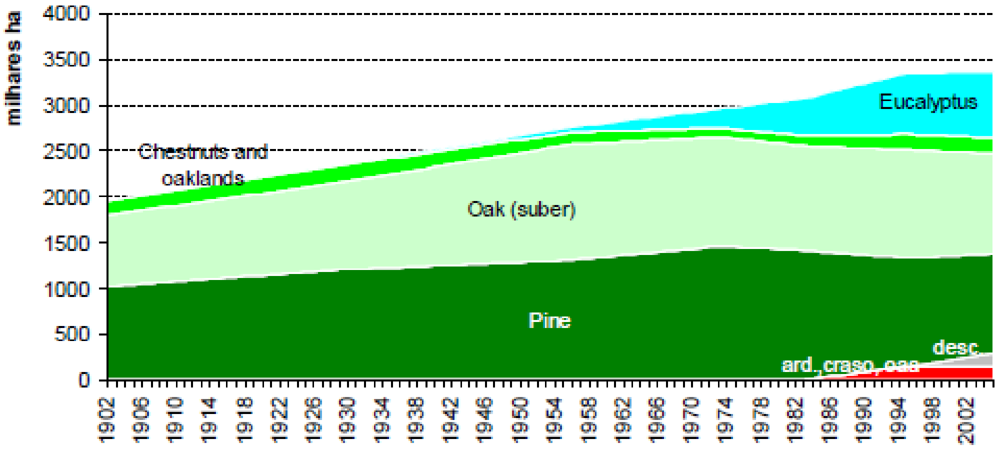


Figure 3. Distribution of forested land in Portugal from 1902-2005 (Oliveira, 2011a).

In thinking about the potential consequences of high fuel loads, but also the imperative of protecting people and property with fire suppression, it is clear that decision makers must tradeoff, be it implicitly via value judgments or explicitly via budget allocations, fuel reduction strategies with fire suppression expansions. While Saveland (1998) suggests that fuel reduction, via prescribed burning, is the fundamental solution to controlling damages from forest fire, one can imagine that decision makers in Portugal must also consider the public pressure for expanded fire suppression forces. For example, inhabitants living on the wildland urban interface (WUI), the transition zone between unoccupied forest and human development, may care less about long-term fire reduction strategy and more about short-term protection from the upcoming seasons' fires.

Strategic challenges to forest fire management in Portugal include many factors beyond simply fuel accumulation. Decision making should also take into account long-term phenomena like climate change, the projected annual growth in the forestry sector, and a wide array of forest-related research, among many other factors. However, this research focuses on fuel accumulation because it is at the center of the human-forest dynamic. The following section discusses relevant operational challenges.

1.1.2 Operational Challenges

Operational decision making in forest fire management, at least as defined in this research, refers to the decisions made within the fire season. The exact range of the fire season varies based on region, but in the northern hemisphere most fire agencies refer to Charlie Phase, from July 1st to September 30th, as the time period of greatest fire risk during the year. While the time horizon of decision making is shorter, lurking variables or relationships unaccounted for can undermine what otherwise appear to be sound management strategies.

Operational challenges to forest fire management in Portugal are primarily complicated by the unusually high number of ignitions that occur during Charlie Phase (Figure 4), where as many as 97% are human-caused (Beighley & Hyde, 2009). The large number of human-caused ignitions makes central management decisions difficult to devise, since the cause of ignition results from several different activities. These include reclassification of the land for urbanization, pyromania, vandalism, speculation on the sale of burnt wood, burning agricultural stubble, and burning to renew pastures (Pereira et al., 2006). Solutions include increased law enforcement, surveillance, fines, and education, among others, yet no single “fundamental solution” has been characterized in the literature.

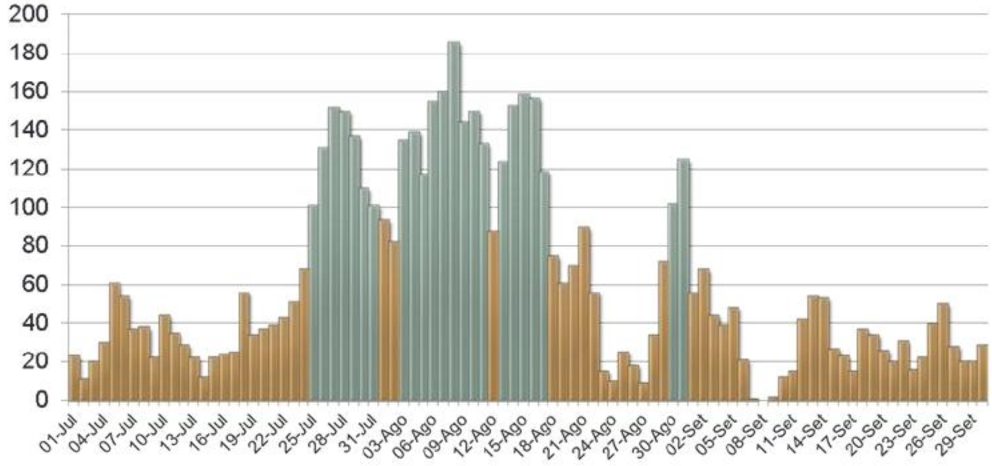


Figure 4. Ignitions per day in Porto district, Charlie Phase, July 1-Sept. 30, 2010 (Pacheco, 2011).

While examining methods for reducing baseline number of ignitions is certainly useful, this research focuses on modeling the consequences of rekindles, or fires that have been insufficiently extinguished and reignite at a later time. In Portugal, fire crews are instructed to suppress the fire in less than 90 minutes (if possible) because after 90 minutes the fire is classified as extended attack, and more scarce resources must be deployed. To fully extinguish a fire, crews must use a combination of water tactics and hand tools; after putting out the surface fire with water, hand tools must be used to extinguish fires burning underneath the top soil around the fire perimeter (this activity is called *mop-up*). Under time constraints and pressure from fire commanders to move onto new fires, crews may utilize only water or prematurely abandon mop-up efforts, which can create conditions for the fire to rekindle hours later (Beighley & Hyde, 2009; Beighley & Quesinberry, 2004). These rekindles represent rework that, while at the present may appear to have been completed, will in the future require scarce resources to be redeployed. The proportion of rekindles across the 18 districts of Portugal varied between 0 and 85% in 2010 (Pacheco, 2011). Such increases over the baseline number of ignitions can greatly stress firefighting capacity, sometimes causing the suppression system to collapse (Pacheco, 2011) as insufficient resources are available to respond to every ignition. At this point fires are allowed to grow as they wait “in queue” for service.

Operational forest fire management decisions encapsulate many more resource deployment complexities than simply rekindles, many of which will be discussed in the literature review in Section 2.1. However, given the prevalence of rekindles in certain districts of Portugal, an in-depth examination of the process by which rekindles occur is warranted for developing system insights into forest fire management operations, specifically the unintended consequences of seemingly rational policies, such as the 90-minute suppression target.

1.2 Research Overview and Objectives

Management of forest fires in Portugal is a technology and policy problem. Fire detection and suppression technologies have become increasingly adept at locating and extinguishing fires quickly. While these technologies provide protection to the people living on the WUI during the fire season, a possible side effect of too much adherence to these technologies is the accumulation of forest fuel, which can result in larger, more severe fires in later years. Technology is at the center of this complicated dynamic between human and ecological systems, its use affected by pressure from the public on governments to keep them safe from fires.

While new suppression technologies may extinguish fires quickly, in the absence of sound firefighting policy they may not extinguish fires *effectively*. High-tech aircraft equipped with water dropping technology are favorable tools for firefighting in Portugal, and elsewhere, because of their ease and mobility. However, without sufficient mop-up following the drop, fires may rekindle, undermining the usefulness of this expensive technology. The relationship between humans (in particular firefighters) and technology is complicated by the institutional policy, and pressure, to extinguish fires as quickly as possible.

Under both strategic and operational circumstances, people are using technology to influence forest fires, but the social systems in which people reside impact how the technology is employed and the extent of its effectiveness. The impact of technology on the frequency and severity of fires in turn leads to new technology decisions. A systems-driven research approach for understanding these complex dynamics is therefore warranted. Thus, the objectives of this research are the following: **(1)** characterize the dynamics of strategic and operational decision processes by building models that capture internal feedback loops and their effect on system performance, and **(2)** assess the implications of these dynamics on policy and management, as well as the barriers to implementation, in order to make recommendations. From these objectives stem the following two corresponding research questions:

- What general system structures capture the underlying dynamics of the strategic and operational forest fire management systems? What can be learned from these structures and dynamics?
- What policy or management approaches can be used to mitigate (or prevent) unfavorable dynamics? How do competing stakeholder objectives, as well as other policy barriers unique to Portugal, impede the implementation of such approaches?

Answers to these questions will provide a richer understanding of the technology-driven dynamics between social and physical systems in forest fire management. Findings will shed light on the unintended consequences of high-tech firefighting solutions, providing valuable insight to policymakers and fire managers alike. Finally, policy recommendations will be made after discussing the challenges of migrating the research findings into action. The following section outlines the research.

1.2.1 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 provides relevant literature review of forest fire management and System Dynamics. Section 2.1 provides a comprehensive review of operations research studies in various functions of forest fire management. Despite being the dominant approach in the field, operations research has some limitations, discussed therein. Section 2.2 provides an overview of System Dynamics, its capabilities and use in various fields, illustrating how it provides a novel perspective to forest fire management problems. Finally, Section 2.3 makes explicit the gaps in current research and the expected contribution of this research.

Chapter 3 explains the System Dynamics model development process undertaken in this research. Section 3.1 compares and contrasts System Dynamics with other simulation approaches, justifying why System Dynamics was chosen to answer the research questions posed. Section 3.2 discusses how general system structures, or archetypes, can be used to frame dynamic problems. Many of these archetypes exist in a wide array of complex problems, but this research applies two to the strategic (suppression versus prevention expenditure) and operational (how to mitigate rekindles) challenges discussed previously. Using these archetypes as a foundation, Section 3.3 develops the logic and mathematics of two simple simulation models.

Chapter 4 provides results of simulations run in each of the models, using numerous graphs and subsections to explain how the feedback loops in the systems cause various modes of behavior over time. Section 4.1 provides results for the strategic model and Section 4.2 for the operational model.

Chapter 5 discusses the results of the simulations. Section 5.1 explains the dynamics operating in each of the two systems, explaining why under certain circumstances the systems operate in various ways. Implications on policy in light of these dynamics are also discussed. Section 5.2 discusses the limitations of the models and conducts a sensitivity analysis on the relationships that have the largest impact on model output. Limitations of System Dynamics in general are also discussed, paying particular attention to the shortcomings of deterministic models.

Chapter 6 discusses how this research can be used toward the development and implementation of actionable policies in Portugal. First, Section 6.1 describes the set of relevant stakeholders and their corresponding functions in the forest fire management system. Section 6.2 discusses impediments to implementation by analyzing the competing objectives of stakeholders and additional social and physical obstacles unique to Portugal. In Section 6.3, this information is synthesized and recommendations for implementing policy are made, including specific next steps in both the strategic and operational domains (detailed in Appendix D: Case Study Research Plan and Appendix E: Rekindle Mitigation Project). Finally, Chapter 7 concludes the research and discusses avenues for future work.

Chapter 2. Literature Review

Forest fire management includes a diverse set of tasks and functions across multiple spatial and temporal scales that together comprise the forest fire management system. This system, its subsystems and components interact with the forest via fire-related costs and forest management objectives, shown in Figure 5. Many different modeling approaches and methodologies have been applied to various components of the forest fire management system, with operations research methods comprising the bulk. While operations research has contributed a vast amount of research to the field, most has focused on narrowly-defined, static problems. The advantage, in short, of using System Dynamics over traditional operations research methods is the ability to model long-run *dynamics* of various policies and decisions. Doing so presents a much broader view of the problem, producing systemic rather than statistically significant insights. This chapter will begin by reviewing select operations research papers. Then, it will review seminal System Dynamics studies, illuminating its general advantages over operations research approaches, but also its limitations. Finally, the chapter will conclude by fusing these reviews to reveal the literature gaps that this research aims to address.

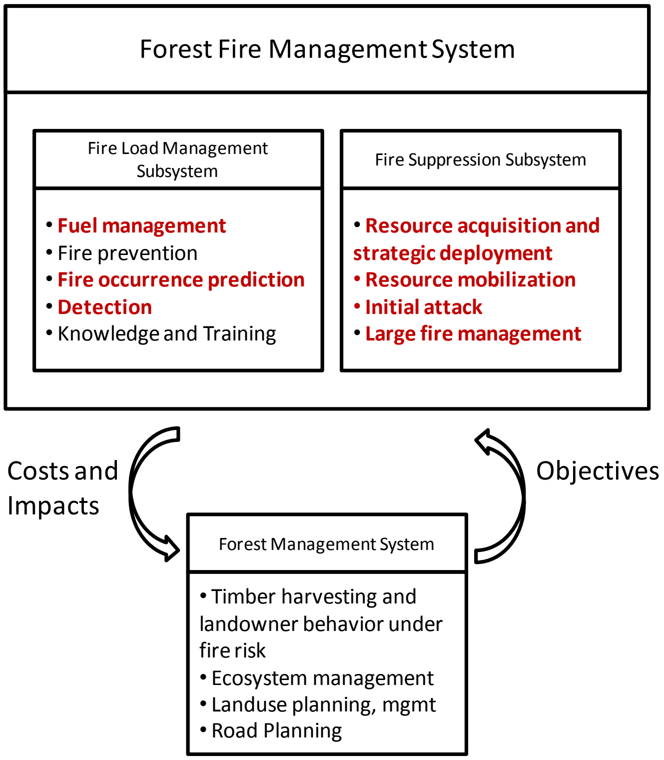


Figure 5. Diagram of forest fire management system, subsystems, representative components, and relation to forest management system, adapted from Martell (2001).

2.1 Operations Research in Forest Fire Management

While Figure 5 paints a complex picture of present-day forest fire management, its research origins are in simple economic models. The earliest of which was the Least Cost plus Damage (LCD) model developed by Sparhawk (1925), used to derive the optimal presuppression expenditure (before fires occur) such that the sum of fire damages and suppression costs (during and after fires) is minimized, which became the foundation for modern forest fire economics. Referring to Figure 5, many define presupppression as including fire occurrence prediction, detection, resource acquisition and strategic deployment, and resource mobilization. Suppression, or the actual act of fighting fires, includes initial attack and large fire management. Thus, Sparhawk (1925) collapsed these various activities into just two categories, presuppression and suppression, asserting that as presuppression increases, suppression costs and fire losses decrease, resulting in a theoretical presuppression expenditure such that the sum of costs and losses is minimized (Figure 6). While analytically simple, the economics have inspired reformulations (Donovan & Rideout, 2003a) and alternative expressions (Rideout & Omi, 1990) of the basic LCD model, now commonly referred to as the Cost plus Net Value Change (C+NVC) model. The following subsections will explore operations research studies in the highlighted subsystem functions of forest fire management in Figure 5.

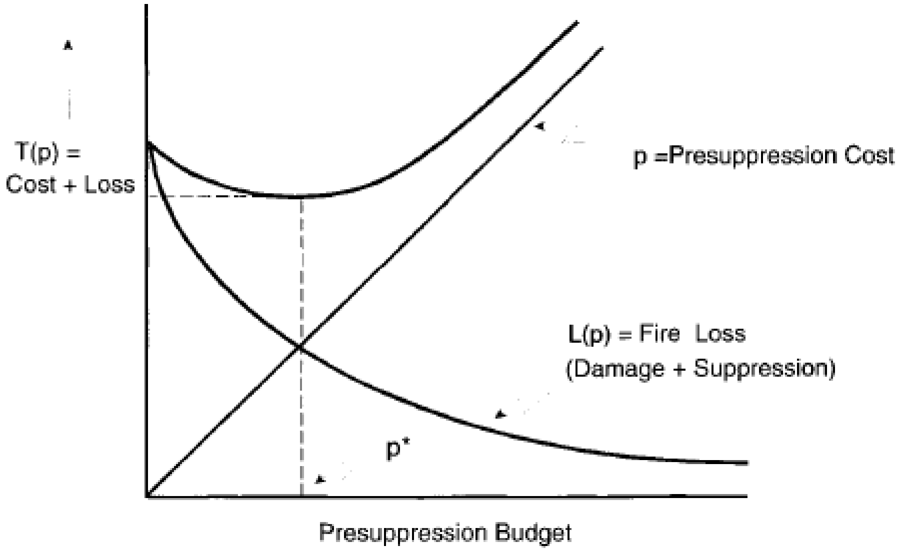


Figure 6. Sparhawk's (1925) least cost plus damage fire economics model, from (Martell, 2001)

2.1.1 Fuel Management

Fuel management seeks to increase the opportunities for successful fire suppression and/or increase ecosystem resilience to fire. This is often achieved by modifying forest vegetation or fuel structure to stop or slow the spread of fires, via fuel break construction (where suppression crews can position their resources), or to reduce the likelihood that fires will occur, via fuel reduction treatments (e.g. prescribed burns, chemical treatment, physical thinning).

The management of fuel breaks has been modeled in several studies. Davis (1965) used a gaming simulation technique and subjective assessments from fire experts to model hypothetical fire-fuel break encounter scenarios to evaluate alternative levels of regional fuel break systems. Harrison et al. (1973) did a decision analysis to predict the expected present cost plus loss of three fuel management policies: no fuel modification, extensive network of conventional fuel breaks, and expansion of a conventional network by widening with periodic application of prescribed fire. Omi (1979) developed a linear programming model that maximized the effectiveness of resource allocation to fuel break construction and maintenance over a 10-year planning horizon using subjective assessments and multiple regression models to estimate break productivity. Finney (2001) used linear fuel breaks, area-wide treatments, and fire spread geometry to design fuel treatment patterns with the maximum effect on forward spread rate.

Optimization of fuel treatments has also been modeled in the operations research literature. Cohan et al. (1983) did a decision analysis to evaluate alternatives comprised of combinations of silvicultural (i.e. timing of thinning and harvesting operations) and fuel treatments on the basis of net present value over a finite planning horizon. Hof et al. (2000) explores spatial optimization approaches to fire and fuel management using a timing-oriented integer programming model that seeks to slow the movement of fire through “protection areas”. Dynamic economic models of prescribed fire use alone (Yoder, 2004) and in combination with prevention education (Butry et al., 2010) have been developed, but they fail to capture the dynamics between social institutions and forest fire damages, a relationship that is significant in Portugal.

2.1.2 Fire Occurrence Prediction

Fire occurrence processes are typically classified into two broad categories – people-caused fires and natural fires, typically from lightning. Cunningham and Martel (1973) showed that it is reasonable to assume that the number of fires occurring in a region each day follows a Poisson probability distribution with an expected value that varies with the weather (described by fire danger rating systems). Martell et al. (1987) used a procedure based on logistic regression to predict the probability of daily people-caused fires, while de Vasconcelos et al. (2001) also used neural network models. Kourtz and Todd (1992) developed a model for predicting daily fire ignitions from lightning using fuel moisture and lightning stroke data. Attempts have also been made to quantify increases in daily fire occurrence under various climate change scenarios (Wotton et al., 2003).

2.1.3 Detection

The role of detection systems, including organized detection (e.g. fixed lookouts, air and ground patrols) and unorganized detection (i.e. the public), is to find and gather information about fires that have ignited to minimize dispatch time, arrival time, and subsequent suppression efforts. Detection planning can be categorized into strategic and tactical decisions, basically representing long-term (i.e. throughout the season) and short-term (i.e. daily) detection planning. On the strategic level, Harnden et al. (1973) designed a combined tower and aircraft detection system that minimized total cost of fire detection and suppression through optimal number and location of towers and frequency, timing, and location of fixed air patrol routes. O'Regan et al. (1975) developed a quadratic programming model that maximized the effectiveness of an airborne infrared detection system. Optimal flight lines were specified in the model such that the expected number of fires detected was maximized for each patrol.

Tactical detection planning concerns optimal search strategies for lookout towers and daily timing and routing of airborne and ground patrols. Kourtz (1973) used a dynamic programming model to route aircraft in order to maximize the expected number of fires detected by a patrol of specified duration. Kourtz and Mroske (1991) formulated the daily patrol routing problem as a multiple salesperson traveling salesperson problem, where aggregate travel time to each patrol destination (or within some designated distance) was minimized given various constraints. With major technological advances in satellites, satellite imagery, and remote sensing, operations research work has largely been replaced by new and improved algorithms for detecting fires across landscapes using satellites and Unmanned Aerial Vehicles (UAVs) (Cuomo et al., 2001; Flasse & Ceccato, 1996; Giglio et al., 2003).

2.1.4 Resource Acquisition and Strategic Deployment

This aspect of the fire suppression system involves deciding what resources to acquire (e.g. air tankers, transport aircraft), where to base them, types of facilities to install at bases, and operation-specific personnel requirements, among other things. Maloney (1973) developed a parametric linear programming model whose objective was to minimize the unit cost of satisfying quasi demand for long term fire retardant by assigning different types of air tankers and associated flying hours to each base. Hodgson and Newstead (1978) formulated the daily air tanker deployment problem as a location-allocation problem where air tanker groups are assigned to bases to maximize coverage of fires and minimize mean fire-to-base distance. MacLellan and Martell (1996) developed a mathematical programming model to identify a home-basing strategy that would minimize the average annual cost of satisfying daily air tanker deployment demands, and Greulich (2003) used a spreadsheet-based approach to optimize air base location. Finally, Donovan (2006) developed a model to determine the optimal mix of federal and contract fire crews in the Pacific Northwest of the U.S.

2.1.5 Resource Mobilization

Resource mobilization models are often intertwined with resource acquisition models, as shown by some of the aforementioned integrated home-basing and daily-deployment models. Daily deployment decisions have been modeled as queuing problems, with fires as customers and air tankers (or bases) as servers. Bookbinder and Martell (1979) considered daily allocation of initial attack transport helicopters to bases given that fires arrived according to a time-dependent, Poisson process and service facilities at each base were modeled as exponential, multi-channel, time-dependent queuing systems; the objective was to minimize the value-weighted maximum expected queue length summed over all bases. Islam and Martell (1998) used a hypercube queuing model to deal with interacting bases (which hadn't been addressed prior), time-dependent fire arrival rates, and Erlang service times in order to minimize initial attack response times. Islam et al. (2009) developed a time-dependent, spatial queuing model to minimize expected virtual response time with air tankers as mobile servers and used a heuristic procedure to help resolve deployment decisions.

2.1.6 Initial Attack and Large Fire Management

Initial attack dispatching decisions include what resources to dispatch to each reported fire and how to prioritize scarce resources when there are multiple fires burning. These decisions often must be resolved quickly and with limited information concerning current and future fire behavior. The decision making associated with initial attack operations is therefore typically subject to the skills, experience, and intuition of the firefighters. Nonetheless, these decisions have been modeled analytically.

Parks (1964) developed a simple model to derive optimal suppression resource allocation to a fire using various fire behavior and suppression productivity parameters, as well as numerous simplifying assumptions. More recent approaches to resource allocation for initial attack and fire containment include integer programming (Donovan & Rideout, 2003b) and deterministic dynamic programming (Wiitala, 1999) models.

Large fire management deals with fires that escape initial attack and continue to burn despite prolonged suppression efforts. Optimizing large fire management is difficult due to the numerous uncertainties, mostly driven by the weather, and agency coordination obstacles that come into play as the fire grows. Finney et al. (2009) did a generalized linear mixed-model analysis to derive large fire probabilities based on a number of fire growth variables, but the model is a highly simplified picture of the large fire management process.

2.1.7 Integrated Forest Fire Management Systems

What has become more common in the recent past is for forest services and fire management agencies to develop integrated forest fire management systems for strategic and operational planning. These systems incorporate initial attack decisions with large fire management for example, but also include other management functions comprising a large decision support framework. They are based in operations research methods, but utilize simulation and algorithms as well to handle more complex fire management problems. Examples include NFMAS in the U.S., LEOPOARDS in Canada, and KITRAL in Chile, among others.

Such decision support tools have been implemented in Portugal with moderate success. At grupo Portucel Soporcel (gPS), a linear programming tool for strategic forest management

(Borges & Falcão, 1999) was used in 1998-99. Between 2002 and 2004, further developments were undertaken to produce an integrated forest management planning tool using heuristics and linear programming (Borges & Falcão, 2000; Ribeiro et al., 2005), but the tool could not be migrated to gPS practitioners and the effort was abandoned. More recent mathematical programming models use heuristics to support a wide range of management and planning problems (Borges et al., 2010; Borges et al., 2008; Reynolds et al., 2008), but their usefulness in practice is still under question.

This research does not seek to develop an integrated forest fire management system of similar quality to the ones in the U.S. or Canada; under time and resource constraints it is simply not possible. However, it does seek to provide new perspective on management problems by taking a long-term, dynamic approach where interactions between social and physical systems are modeled explicitly. While the ability of operations research models to yield optimal management solutions is attractive, their dependence on numerous simplifying assumptions can limit their use in practice (Martell, 1982). In particular, such models typically ignore complex feedbacks that impact forest fire management from one year to the next. System Dynamics is well-suited for modeling such feedbacks and subsequent long-run behavior; the following section briefly reviews the history, advantages, and limitations of System Dynamics.

2.2 System Dynamics Models: A Review

System Dynamics is a modeling approach grounded in systems thinking, which is basically a problem-solving approach that views problems as parts of an overall system rather than existing in isolation. The notion that problems are part of a system is not a groundbreaking discovery; plants, trees, animals, and insects comprise natural ecosystems and people, processes, technologies and hierarchical structures comprise organizations. We're familiar with systems, but despite this knowledge problem-solving in business, government, diplomacy, and other domains has often ignored the interconnectedness of things and sought to solve problems without explicitly considering the impacts that may ripple across other parts of the system.

In his seminal article in the Harvard Business Review, Forrester (1958) formalized a systems-driven approach to problem-solving that came to be known as System Dynamics. The purpose of the paper was to inform industrial companies on how to anticipate the effects of decision and policies, organizational forms, and investment choices through explicit consideration of the interactions between capital stocks, materials, money, manpower, and the flow of information. He expanded on these interactions ten years later to develop the still widely cited “market growth model” that shows how different modes of growth behavior arise from endogenous feedback structures in an industry or market (Forrester, 1968a). Jay Wright Forrester, then a professor at MIT, went on to publish numerous books (and many other articles) advancing his systems approach (Forrester, 1968b) and applying it not only to industry (Forrester, 1961), but also city planning (Forrester & Collins, 1969) and world population-resource dynamics (Forrester, 1971).

While consistent in his approach, Forrester’s models of complex systems were not always 100% accurate, and this is a reality of modeling regardless of approach. For example, *The Limits to Growth*, a highly controversial book published in 1972 and commissioned by the Club of Rome, developed a System Dynamics model of the world’s population, natural resources, and economy (called World3) predicting world food shortages by the end of the 20th century. Such shortages of course never occurred, due to the technological advancements of the Green Revolution as well as other factors simply not accounted for in the original model. The lesson from this example is an important one. System Dynamics models are useful for the insights they generate to managers of complex systems or organizations, not for precise numerical results or predictions. The logic driving World3 was largely sound; even with technological development there is a carrying capacity (in terms of natural resources) of the planet that cannot support increasing standards of living indefinitely, particularly in light of exponential population growth. Communicating these dynamics to decision makers and getting them to appreciate the implications, what Sterman (2000) calls altering their *mental models*, is thus a much more important goal than fruitlessly seeking predictive power.

Despite the lack of numerical precision, System Dynamics has been applied extensively in a variety of disparate fields. Examples include supply chain management (Angerhofer & Angelides, 2000), education (Kennedy, 2009), public health (Homer & Hirsch, 2006), water resource management (Winz et al., 2008), electric power systems (Steel, 2008), and global climate change (Sterman, 2011) to name a few. The System Dynamics Society, a professional society with its own conferences and publications, is a good reference for additional articles and projects in other fields.

What many System Dynamics models, regardless of application, try to illuminate are the side effects or unintended consequences of seemingly rational decisions or policies. Consider again the two problems of forest fire management in Portugal explored in this research. On the strategic end, decision making has expanded the suppression capacity of the country in an effort to reduce the frequency and severity of fires. On the operational end, fire crews seek to minimize their response time at any one fire in an effort to respond to more fires throughout the day. Both policies seem reasonable, but as Sections 1.1.1 and 1.1.2 pointed out, there are side effects or unintended consequences of these policies that actually exacerbate the problem and may undermine other solutions. Sterman (2000) calls this phenomenon *policy resistance*.

Despite the policy resistance of systems to seemingly rational decisions, managers often adhere to the flawed policies due to entrenched mental models of how the system works, institutional or social pressures, or some form of principal-agent problem where incentives are not aligned. Either way, what happens is that the system gets trapped in a vicious self-reinforcing cycle whereby the problem continues to get worse yet the solution remains the same. Interestingly, in the business literature this phenomenon is called *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 problem. As will be shown in this research, the so-called “firefighting trap” that arises due to policy resistance and a variety of other factors occurs in both the strategic and operational forest fire management systems in Portugal. This behavior is not new, nor is it unique to forest fire management (despite the fitting name), and has been modeled in numerous other contexts. The following section uses two illustrative examples from new product development and manufacturing plant maintenance to give credence to the existence of the phenomenon and provide a theoretical underpinning to this research.

2.2.1 The Firefighting Trap

Repenning (2001) defined firefighting as the unplanned allocation of resources to fix problems discovered late in a product’s development lifecycle. He showed that it can be a self-reinforcing phenomenon once it begins, where new concept development degrades over time as finite resources are continually applied to product design and rework (Figure 7). As a result, the system gets trapped in a state of continual corrective action and new concepts become a rarity. This generalized rework structure forms the foundation of the operational model (Section 3.3.2).

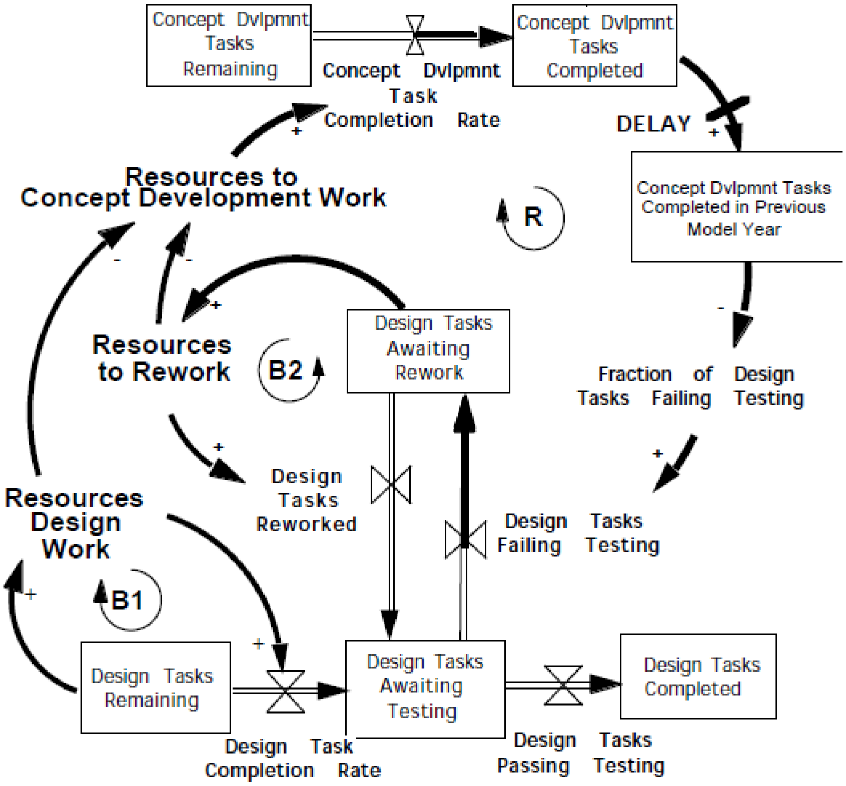


Figure 7. Firefighting in new product development (Repenning, 2001).

Sterman (2000) has characterized this phenomenon in manufacturing plant equipment maintenance, where managers take action for short-term gain as opposed to long-term profitability (Figure 8). Specifically, they are loath to take down the plant for maintenance since it means foregone revenues in the short-term. Wear and tear on the equipment causes more plant downtime due to reactive maintenance, which further cuts into resources devoted to preventive maintenance. As a result, the long-term state of the system degrades and plant profitability declines. The structure of the manufacturing plant system forms the foundation of the strategic model (Section 3.3.1).

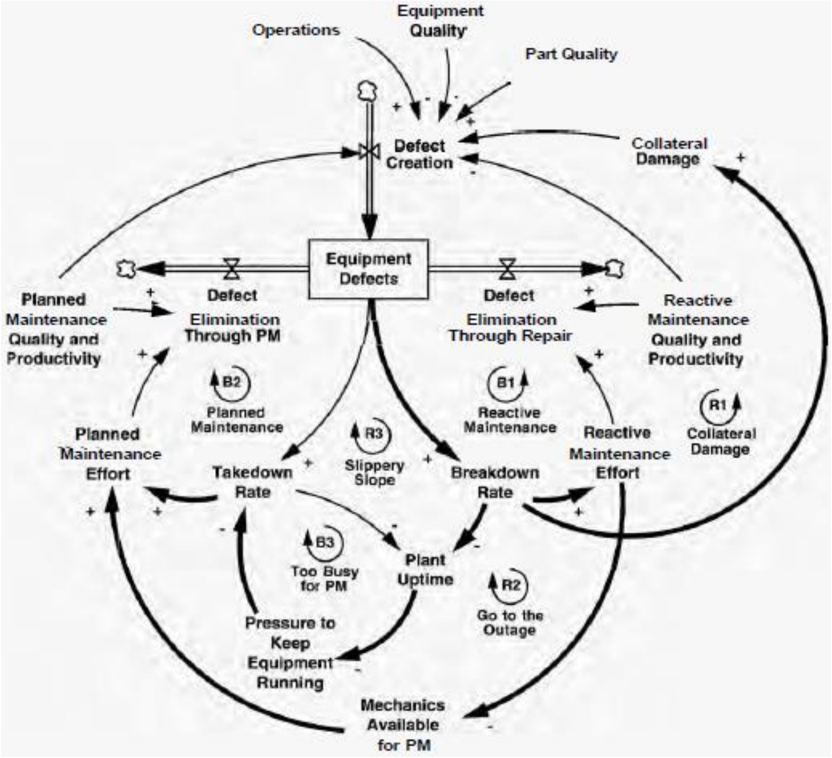


Figure 8. Firefighting in manufacturing plant equipment maintenance (Sterman, 2000).

Whether it's in new product development, plant maintenance, or forest fire management, reactive over proactive decision making leads to worse system performance in the long-run. It is not surprising (and also somewhat amusing) that the firefighting trap, a phenomenon initially applied to business dynamics, also has application to decision making in forest fire management.

2.3 Literature Gaps and Expected Contribution

Researchers continue to use economics, operations research, simulation or some combination thereof to build prescriptive models of forest fire management. Simulation in particular allows forest agencies to generate large samples of "what if?" scenarios in order to guide suppression expenditures, fuel treatments, and dispatch strategies under the uncertainty of future fire activity and individual fire extents. While incredibly useful, such models often completely ignore how social, political, or institutional systems impact the ability of agencies to carry out their fire management programs. For instance, is it politically feasible to conduct major fuel treatments while slashing the suppression budget, even if the model tells you that it is optimal to do so? Assuming the dispatch strategies are correct, can we be assured that fire agency politics won't diminish the ability of the crews to extinguish the fires? While simulation is a useful tool, current approaches have not sufficiently modeled the impact, let alone the feedback, of social systems on fire management regimes.

As Sections 1.1.1 and 1.1.2 indicated, social systems in Portugal, more specifically human decision making, impact the physical forest system via the attempt to control forest fires with technology. While some of these dynamics have been characterized in the literature, gaps remain in trying to quantify them in a simulation environment. The use of System Dynamics to qualitatively measure the impact of socio-physical dynamics on forest fires therefore represents a novel research approach in the field of forest fire management.

This research will contribute to forest fire management by increasing practitioner understanding of the feedback loops affecting strategic and operational management systems, providing insight into how best to address these dynamics via policy and management improvements. In general, System Dynamics models are useful as learning exercises and communication tools in order to challenge entrenched beliefs and preexisting mental models. They increase visibility of indirect or second-order consequences, raising awareness about lurking variables that aren't given as much attention in policy or management decisions.

Finally, this research will contribute to the field of System Dynamics generally through investigation of the firefighting phenomenon in forest fire management. Besides Saveland's (1998) characterization of the policy resistance that stems from fire suppression, which notably has been referenced elsewhere in the System Dynamics community (Sterman, 2006), the field has largely been unexplored with Systems Dynamics. Thus, the fully functioning simulation models developed in this research are themselves a contribution. The following chapter provides detailed description of the model development process for both the strategic and operational management systems.

Chapter 3. Model Development

The FIRE-ENGINE project steering committee stipulated that System Dynamics be utilized in the project to model the interaction between stakeholders and the forest. Chapter 20 showed that System Dynamics can provide new and useful insights over the operations research literature, but there are multiple simulation platforms and software for modeling the complex processes and systems of forest fire management. As was shown, some have been incorporated in decision support systems for regional fire management agencies. Why ultimately is System Dynamics the best tool for answering the research questions of this thesis? Simulation may be warranted over purely analytical models, but why not use Discrete Event Simulation or Agent-Based Modeling, for example? There are many reasons, but the answer lies primarily in the need to explicitly model feedback loops, and their effect on system behavior over time.

This chapter describes development of the two System Dynamics (which may henceforth be referred to simply as SD) models used to explore strategic and operational forest fire management problems. Section 3.1 explains the rationale for why SD, as opposed to other modeling approaches, was chosen for this work. Section 3.2 describes two general system structures, or archetypes, that capture the underlying dynamics of the strategic and operational forest fire management systems. Finally, Section 3.3 develops the logic and mathematics of the two models built to quantify the outcomes of the dynamics operating in these systems.

3.1 Choosing the Right Modeling Approach

Selection of the right modeling approach depends ultimately on the question attempting to be answered. Sometimes, a well-framed question will make it immediately evident which modeling route to take. However, most of the time even well-framed questions can warrant several different approaches; what will vary is the nature of the answers to the questions. In addressing problems in complex systems, or what Cutcher-Gershenfeld et al. (2004) more comprehensively refer to as complex, large-scale, integrated, open systems (CLIOS), no single approach, or model, will provide an unambiguous answer to the question at hand. In other words, no single model can capture all of the complexity present in a CLIOS *and* provide meaningful, or even interpretable, results. Much more likely is that each approach will generate unique insights into the workings of the system, or the conditions under which the system behaves in certain ways, and by extension the conditions under which certain decisions should be made. If validated by real and complete data, some models may generate very specific recommendations for decision making. While these types of models may be attractive to decision makers, it is worth qualifying this attraction with the following timeless modeling adage: “All models are wrong. Some models are useful”.

Forest fire management, both generally and specifically with regard to the conditions in Portugal, is an example of a CLIOS. Multiple institutions, ministries, and organizations are responsible for management; there are multiple feedbacks linking human decisions with forest outcomes; the impacts of fire are large, affecting the entire country both directly and indirectly; these characteristics result in social, political, and economic consequences. Given all of this complexity, we cannot expect one approach to model the entire system; doing so wouldn’t be useful anyway. As stated previously, selection of the right approach depends on the question trying to be answered. Table 1 compares three major simulation approaches along a variety of different dimensions, showing under which conditions a certain approach may be favorable.

Table 1. Comparison of SD, DES, and ABM modeling approaches, adapted from Chahal & Eldabi (2008), Love et al. (2008), and Tako & Robinson (2009).

Modeling Aspect	**System Dynamics (SD)**	**Discrete Event Simulation (DES)**	**Agent-Based Modeling (ABM)**
Nature of Problems Modeled	Strategic	Tactical/Operational	Strategic
System Representation	Holistic view, emphasis on dynamics and emergent behavior	Analytic view, emphasis on system performance	Holistic view, emphasis on emergent behavior
Model Entities	Stocks and flows connected by causal loops and delays	Entities, resources governed by flow charts	Agents defined by rules of interaction
Spatial Relationship b/w Entities	Not represented in model explicitly	Distance can be calculated to drive system logic	Space between agents can be key driver in model
Complexity	Wide focus, general and abstract systems	Narrow focus with great detail	Narrow focus on agent interaction, wide focus on system behavior
Data Inputs	Quantitative and qualitative, use of anecdotal data	Quantitative based on concrete processes	Quantitative and qualitative
Randomness	Stochastic features less often used (average of variables)	Use of random variables (probability distributions)	Stochastic features less often used (decision rules)
Feedback	Explicitly modeled through causal loops	Can be implicitly modeled through flow chart	Implicitly modeled through agent behavior
Model Results	Provides a full picture of system performance	Provides statistically valid estimates of system performance	Provides a full picture of system performance
Role of Simulation	SD models used as learning laboratories, allow managers to run models in gaming environment	DES models used less as learning tools and more for decision support	ABM models also used as learning laboratories in gaming environments

By referring back to the research objectives and questions of Section 1.2, it is evident that underlying dynamics and feedback structures are key features to be explored in this research, indicating that SD is an appropriate approach. However, other aspects inform this decision. Because numerous social influences exist in the forest fire management system, from public pressure to managerial goals, a holistic modeling approach can lead to revelatory insights at a systemic level. Such insights, while not necessarily numerically valid, would not be achievable if focusing exclusively on a narrow component of the system, such as fire suppression. It is worth noting that while the problem of rekindles in Portugal is deemed an operational challenge in this research, SD can still be used to explore feedback effects in the system. Thus, while DES may more often be used for operational problems, the presence of social (or qualitative) influences on system performance makes SD a valid approach as well. Concerning the complexity dimension, the following section will show how a holistic view allows general system structures, applicable in many contexts, to be applied to forest fire problems in Portugal. Finally, developing high-level SD models can facilitate discussion with managers and decision makers about policy improvements, which is an important objective of both this research and the FIRE-ENGINE project as a whole.

3.2 System Archetypes in Forest Fire Management

Systems theory, the interdisciplinary study of systems in general, seeks to uncover principles or structures that can be applied to all types of systems. A “system” is a very broad concept, often ambiguous, but generally it is a group of interacting, interrelated, and interdependent components that form a complex and unified whole. In the systems theory literature systems refer specifically to *self-regulating* systems. In other words, the state or function of the system is self-adjusting through the presence of feedbacks among the components. Causal loop diagrams, while ultimately a rudimentary tool, are useful for conceptualizing the feedback structures of such systems. Self-regulating systems are found in nature, human bodies, global ecosystems, and can also be identified in organizations, businesses, and bureaucracies. The difference is that the feedbacks aren’t governed by physics, chemistry, and biology but instead by social, political, and institutional forces. While harder to define, let alone encapsulate in mathematical equations, such forces nonetheless interact with the system entities and drive overall system behavior.

This research has identified two systems, one strategic and one operational, whose behavior and subsequent impacts are central to forest fire management in Portugal. The following two sections apply general system structures, often called archetypes, to these systems. Archetypes alone are not sufficient models, but they help form the conceptual and structural foundation for more complex model development (in Section 3.3). Furthermore, archetypes can serve as diagnostic tools, helping managers recognize existing patterns of system behavior and gain insight into underlying system structures from which archetypal behavior emerges (Braun, 2002; Kim, 1993). Finally, archetypes are also useful as prospective tools, whereby managers can test whether alternative policies produce archetypal behavior (Braun, 2002; Kim, 1994).

3.2.1 "Shifting the Burden" in Strategic Forest Fire Management

Under the "Shifting the Burden" archetype (Figure 9), there is a tension between the attraction (relative ease and low cost) of devising symptomatic solutions and the long-term impact of fundamental solutions aimed at correcting underlying structures producing the symptoms in the first place (Braun, 2002). There is a balancing loop (B1) between the problem symptom and the symptomatic solution. In other words, as the problem symptom increases, the symptomatic solution serves to decrease the symptom. There is also a balancing loop (B2) between the problem symptom and the so-called fundamental solution. Unfortunately, the corrective impact of the fundamental solution occurs with a delay (indicated by the hash marks on the arrow), which often makes the symptomatic solution favorable. However, the symptomatic solution produces a negative side effect that undermines the fundamental solution and further decreases its ability to curtail the problem symptom; this dynamic reinforces the symptom over time (R1).

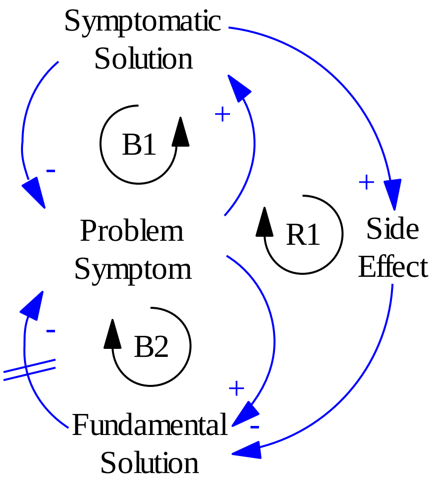


Figure 9. General structure of the "Shifting the Burden" archetype (Braun, 2002).

Figure 9 should look familiar to Figure 2, the causal loop diagram of forest fire management developed by Saveland (1998). In Figure 2, the problem symptom is fire damage, the symptomatic solution is fire suppression, the fundamental solution is prescribed fire, and the side effect is fuel accumulation. The underlying dynamics are the same, though Saveland (1998) also includes the reinforcing effect of fuel accumulation on fire damages via larger, more severe fires in the future.

While many experts in the fire community contend that too much fire suppression can lead to worse fires in the future as a result of increased fuel accumulation, others posit that this is not the case. Some authors argue that the probability of larger fire events is independent of fire suppression efforts and responds mainly to extreme weather (Keeley & Fotheringham, 2001; Keeley et al., 1999; Moritz, 1997; Moritz et al., 2004). While this may be true in certain regions or for certain vegetation types, simple logic tells us that as more fires are prevented from occurring, certain areas of forest will not burn and as a result fuel will accumulate over time. Since it is well-established that fuel load, in addition to weather, drives fire spread (Rothermel, 1983), we can assume that at least to some degree more fire suppression, and thus more fuel, leads to larger fires upon ignition. This assumption and the archetypal behavior that emerges as a result, form the basis of the SD model developed for strategic forest fire management in Section 3.3.1.

3.2.2 "Fixes the Fail" in Operational Forest Fire Management

"Fixes that Fail" is a system archetype that is structurally similar to "Shifting the Burden" in that the managerial response aimed at the problem symptom results in unintended consequences (Figure 10). However, there isn't a clear dichotomy between a symptomatic and fundamental solution, where the problem symptoms worsen despite the symptomatic fix. Instead, the problem symptoms worsen *because* of the fix, yet often with a delay (R1). In other words, the fix may be a perfectly adequate solution under certain conditions or short time horizons, thus providing a balancing effect (B1), but may become problematic in the long-run or under extreme circumstances.

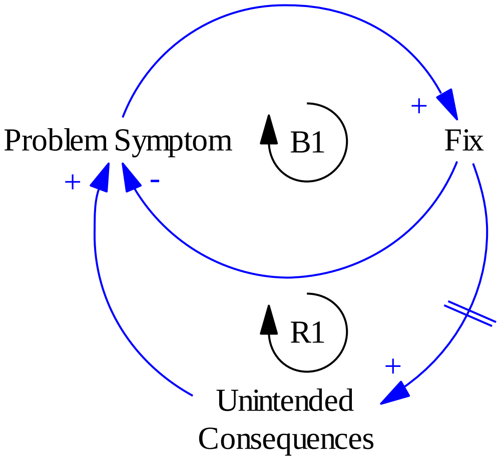


Figure 10. General structure of the "Fixes that Fail" archetype (Braun, 2002).

As was discussed in Section 1.1.2, fire crews in Portugal are instructed to suppress fires in less than 90 minutes if possible. On the surface, this is a useful goal for ensuring high throughput of extinguished fires through the system. And, if ignitions are low and adequate resources available, abiding by this target may be sufficient for managing fire activity, even if some rekindles occur. The unintended consequences manifest during days of high ignitions, such as Charlie Phase, where the pressure on firefighters to extinguish fires quickly and move on to new ones may result in insufficient mop-up at the current site. Insufficient mop-up may lead to future rekindles, additional pressure on firefighters, and thus further reinforcement of the problem.

A call center for IT repairs is a useful analogy, borrowed from Duggan (2009). Consider a manager who wants to incentivize his operators with a financial bonus if they meet a system-wide target for call time. The goal is for end-to-end repair times to drop, but in reality they actually increase. The reason is that the quality of repair information declines as call time decreases, resulting in the same customers calling back for help with the same problems. Thus, while the system-wide target may appear to be a sound management strategy, in the end it increases end-to-end repair time as operators provide inadequate service during the shorter calls. This general system structure and archetypal behavior forms the basis of the SD model developed for operational forest fire management in Section 3.3.2.

3.3 From Archetypes to SD Models

The following two sections develop the causal and mathematical details of the strategic and operational SD models. These models are built around the aforementioned system archetypes and informed by semi-structured interviews and discussion with Portuguese (and American and Canadian) fire experts, some secondary data sources, as well as basic fire science. The models are simple, and where data is lacking there are informed guesses about functional relationships between variables. The logic of these relationships is sound, making all dynamic behavior, irrespective of magnitude, significant and meaningful within the scope of this research.

3.3.1 Strategic SD Model

As Table 1 indicated, System Dynamics models are governed by the quantities accumulating in *stocks* net of all inflows and outflows. While more complex SD models have many stocks, a surprising amount of insight can be gained through the modeling of one stock, particularly if that stock is impacted by multiple variables and feedback loops. Stocks represent the *state* of the system, in that the behavior of all other variables in the system can ultimately be traced back to the stock. As was hypothesized by Saveland (1998) and many other fire experts, the amount of fuel in the forest determines, in part, the severity of future fire activity. While weather is also an important indicator of fire severity, in particular spread, it is not an endogenous variable to human decision making about forest fire management (all discussion of anthropogenic climate change aside). Forest fuel, on the other hand, is a variable that is both affected by human decisions and in turn affects further human decision. Thus, forest fuel is the state of the strategic forest fire management system.

Figure 11 is an aggregated representation of the strategic SD model; it illustrates the high-level dynamics occurring within the system, which consists broadly of the physical and political subsystems. Within the physical system, fuel accumulates according to some growth rate. As fuel load increases, so too does fire severity, which increases burned area per year and subsequently decreases the fuel stock through burning. This naturally occurring balancing loop is titled *Native Fire Regime*, and it represents the basic ecosystem dynamics of a forest undisturbed by human influence.

The political system represents the simplified introduction of human decision making into forest fire management. In Portugal, as well as other civilized fire-prone countries, humans have attempted to control the frequency and severity of fires through better fire suppression capability. Thus, as burned area per year increases, there is more pressure to control the fire (so that people, property and industry can thrive near the forests). This leads to more suppression expenditure and subsequently shorter fire durations as crews can extinguish fires faster and more effectively with better suppression technologies. With shorter fire durations, burned area per year goes down, representing the balancing impact of the *Fire Control* loop.

There is a side effect, however, of increased suppression expenditures. As expenditures increase, the amount of resources available to prevention activities, such as fuel management and prescribed fire, decreases under a finite budget assumption. Thus, as prevention resources decrease, preventative removal of forest fuel goes down and the fuel stock increases. This reinforcing loop, titled *Prevention Resource Scarcity*, illustrates one of the side effects of fire policy built around fire exclusion. Note that this is not the same side effect of fire exclusion that Saveland (1998) and others conjectured, namely that the mere prevention of all small and medium fires from burning results in more accumulated fuel and therefore more severe future fires. Nonetheless, it is an important side effect that appears to have manifested in Portugal over the recent years, and it is still demonstrative of the “Shifting the Burden” archetype given that preventative fuel removal suffers at the expense of more suppression expenditures. The remainder of this section will explain the mathematical details of the relationships comprising the full, disaggregated SD model.

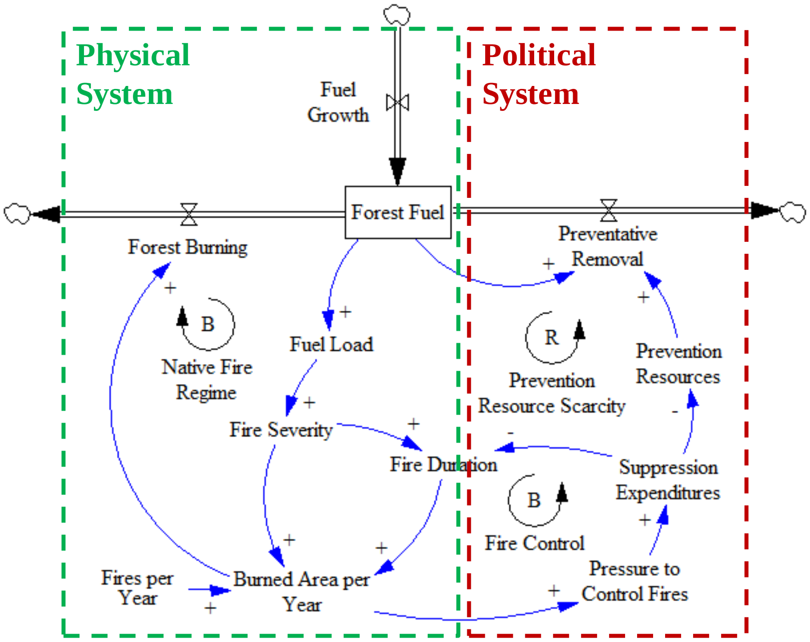


Figure 11. Aggregated SD representation of strategic forest fire management system.

The Physical System Explained

Figure 12 is a simple representation of the forest system in Portugal and its interaction with forest fires over time. Using simplifying assumptions and basic fire science, it produces yearly burned area in the absence of human control and decision making. *Forest Fuel* accumulates according to a constant exogenous flow, *Fuel Growth*, and decreases via *Forest Burning,* which stems from natural, human-caused, or accidental forest fires. The amount of forest burning that occurs each year is determined by the fuel load and the amount of forest area burned. *Fuel Load* is defined as the quotient of *Forest Fuel* and *Total Forested Area*, thus the model is aspatial and implicitly assumes that fuel accumulates uniformly over the *Total Forested Area*. The units for *Fuel Load* are metric tons per hectare, consistent with the measurements of fuel load conducted for experimental burns in Portugal (Fernandes, 2001; Fernandes et al., 2009).

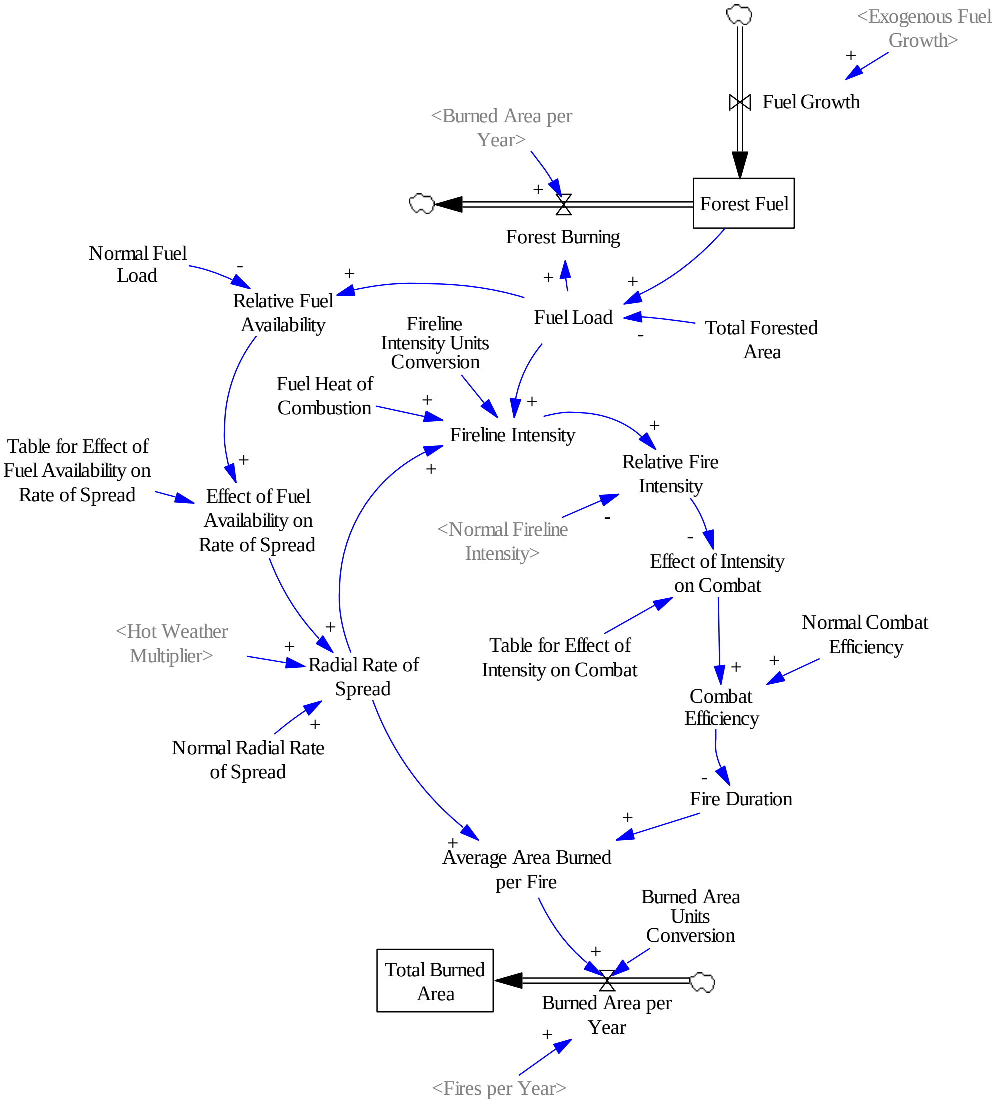


Figure 12. SD model structure of the physical system in strategic forest fire management.

Modeling relationships in which a physical equation does not exist requires the use of table functions in SD, which relates a normalized input to a dimensionless output. Table functions are also useful for building nonlinear or discontinuous functions based on empirical data or qualitative evidence. Using them often requires definition of “normal” or baseline values on which to normalize the inputs and multiply the outputs of the function. These normal variables sometimes represent average values under standard or business-as-usual scenarios, e.g. standard operating procedures in a business or organization. They are also used to initialize a system in equilibrium, which can be a contrived concept in complex systems with interacting social and physical elements (instead, disequilibrium is likely the norm). As such, these values can be arbitrary, but their selection does not impact the systemic insights gained through modeling. The *Table for Effect of Fuel Availability on Rate of Spread* is the table function relating *Relative Fuel Availability* (*Fuel Load/Normal Fuel Load*) to the *Effect of Fuel Availability on Rate of Spread* (a dimensionless output). Results from Fernandes et al. (2009) indicate that rate of spread is roughly proportional to the square root of fuel load, though isolating this relationship can be difficult given that most fuel descriptors (others include fuel depth, vegetation cover, and moisture content) are correlated. Nonetheless, this relationship is used in the table function (Figure 13).

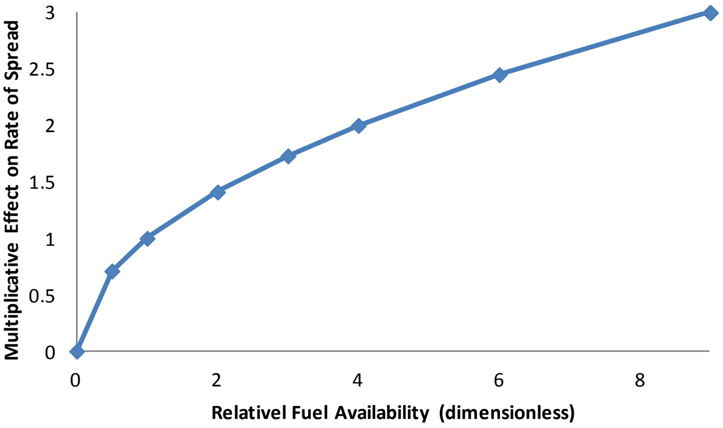


Figure 13. Table function for the effect of relative fuel availability on radial rate of fire spread.

Radial Rate of Spread is calculated by taking the product of the *Normal Radial Rate of Spread*, *Effect of Fuel Availability on Rate of Spread*, and the *Hot Weather Multiplier*. The multiplier is an annual index of weather conditions represented by the average dryness of fuel in a given fire season (year), and was simulated as a random variable that follows a normal probability distribution, as done in Li et al. (1997). While sudden changes in wind velocity can drastically affect the rate of spread of an individual burning fire, this model measures aggregate fire activity and thus all variables, including the weather multiplier, are aggregate measures taken over the entire year.

Fireline Intensity, also known as Byram's fireline intensity or frontal fire intensity, is the rate of heat energy released per unit time per unit length of fire front, regardless of depth of the flame zone (Byram, 1959). Larger fireline intensities make fire suppression more difficult, leading to longer and potentially more severe fires. Byram's fireline intensity I (kW/m) is calculated according to Eq. (1), where H is the fuel heat of combustion (kJ/kg), w the fuel load consumed (kg/m^2), and r the rate of spread (m/s). Necessary unit conversions in the model are completed through the variable *Burned Area Units Conversion*.

$$I = Hwr \tag{1}$$

The *Fireline Intensity* variable represents the reduction in firefighting combat efficiency that comes with increased fire intensity. For example, direct attack with hand tools and assured control of prescribed fire is possible when intensity is less than 400-425 kW/m (Chandler et al., 1983; Hodgson, 1968). Heavy mechanical equipment can usually control a fire if intensity is below 1700-1750 kW/m, though spot fires can become serious at 2000-2100 kW/m, and fires are completely uncontrollable when intensities exceed 3500-3700 kW/m (Chandler et al., 1983). The table function in Figure 14 expresses this relationship since efficiency itself is a dimensionless term and the exact effect of fireline intensity on fire suppression efforts is not well understood beyond generic categorization. The function assumes a linear decrease in combat efficiency with rising fire intensity.

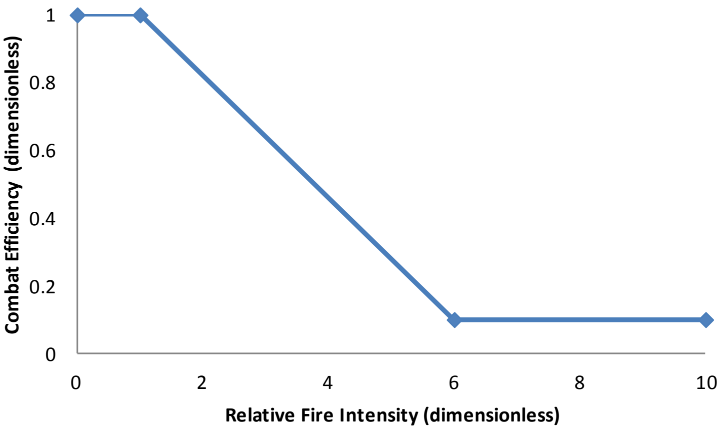


Figure 14. Table function for the effect of fire intensity on combat efficiency.

Combat Efficiency decreases the average duration of fires through increased suppression capability and action. Its effect on *Fire Duration* is explained in the political system next. *Average Area Burned per Fire* is calculated by assuming that every fire grows as a circle. The product of *Radial Rate of Spread* and *Fire Duration* gives the radius of each fire, so calculating area is straightforward. As mentioned above with regard to wind velocity, the scale of the analysis focuses on yearly aggregate impacts, ignoring the distribution of individual fire durations and using averages instead. Ultimately, every fire in the model behaves in the same way, i.e. same fireline intensity, same rate of spread, and same duration. While this is certainly a departure from reality, it is sufficient for modeling the high-level dynamics between the social (political) and forest (physical) systems. Single extreme fires cannot be modeled explicitly, but single extreme fire seasons can, which is ultimately the impetus for subsequent government action.

Given some number of *Fires per Year*, which can be held constant or fluctuate randomly with the weather, *Burned Area per Year* can be calculated by taking 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 Political System Explained

The political system encapsulates management action that is taken given fire damages from the previous year (Figure 15). To qualitatively inform the causal relationships of the political system, semi-structured interviews with Portuguese fire experts and gPS officials were carried out during research time spent in Portugal. They indicated that at the national level policymakers have continued to increase capacity of suppression technologies; a report from the Institute of Agronomy in Lisbon indicated the same (ISA, 2005). Many experts from academia, industry, and forest owners' associations in Portugal 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 airtankers, because they resonate emotionally and psychologically with the public opinion.

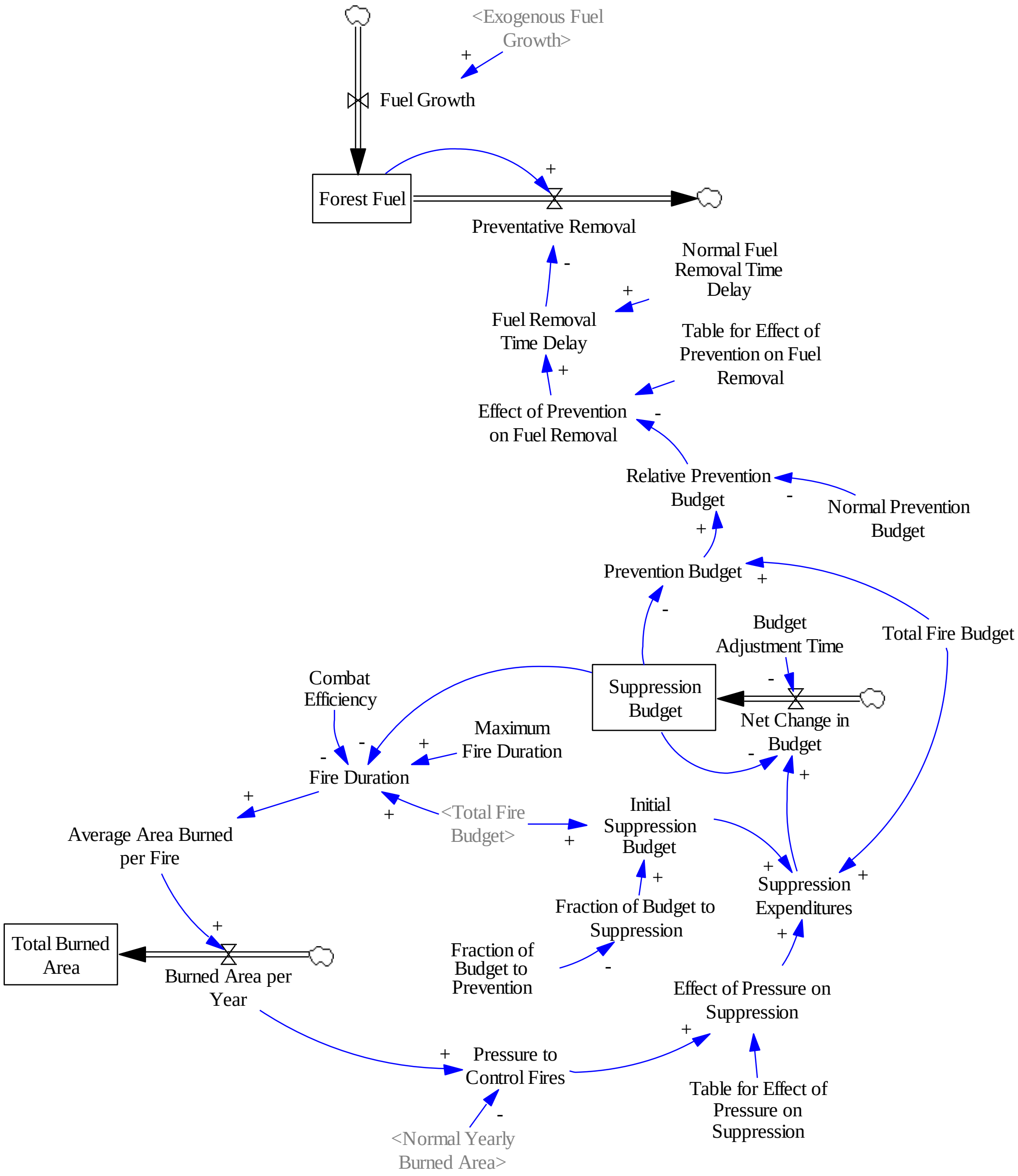


Figure 15. SD model structure of the political system in strategic forest fire management.

A dimensionless variable, *Pressure to Control Fires*, is defined as the quotient of *Burned Area per Year* and *Normal Yearly Burned Area*, where the latter variable represents yearly burned area under equilibrium conditions (i.e. *Fuel Growth* = *Forest Burning* + *Preventative Removal*). Using a table function, the *Table for Effect of Pressure on Suppression* variable relates the pressure on government to control fires to the expenditure on suppression resources over what is considered normal (Figure 16). The shape of the function is a matter of debate. Some experts suggest that it may even resemble a step function. In other words, once a threshold area is burned in a given year, expenditures on suppression resources jump to a higher level. While the exact nature of such a function is difficult to characterize, a steeply sloped linear function is used to demonstrate the sensitivity of governmental spending to forest fire related damages.

Figure 16. Table function for the effect of pressure to control fires on suppression expenditures.

A first order information delay represents the budgeting process for suppression expenditures, shown in Eq. (2). This is essentially a smoothing function of the suppression expenditure demanded via pressure from the public. Such delays are widely used in stock and commodity forecasting to filter out short-term fluctuations in prices (Sterman, 2000).

$$\text{Net Change in Budget} = \frac{(\text{Suppression Expenditures} - \text{Suppression Budget})}{\text{Budget Adjustment Time}} \qquad (2)$$

When expenditures change due to the effect of last year's fire season, they are compared against the current budget and altered accordingly given the adjustment time required to pass new budgets, which is assumed to be three years. The rationale behind using this structure is that despite the sensitivity of government to fire damages, in reality the budget adjustment process can be slow, which dampens the budgetary impact of a particularly bad fire season. However, it is worth noting that under extreme circumstances, i.e. a catastrophic fire season, these conditions may not hold.

Increasing the *Suppression Budget* is synonymous with increasing suppression resources used to enhance firefighting capability, thus driving down average fire duration and decreasing forest burning (this is the balancing mechanism of the *Fire Control* loop from Figure 11). The effect of more suppression resources on fire duration is informed by the LCD model (Sparhawk, 1925), namely that duration will decrease at a decreasing rate as suppression expenditures increase. In the LCD model it is actually the sum of suppression costs and fire damages that decrease at a decreasing rate, not fire duration, though Martell (2001) points out that with more resources (e.g. firefighters), response times are reduced, resulting in a decreased likelihood that fires will escape initial attack, and therefore lower fire damages and suppression costs. Thus, given that the two are related, applying the theory to fire duration seems reasonable. Eq. (3) defines *Fire Duration* (FD).

$$\text{FD} = (\text{Maximum Fire Duration})\, e^{-\text{Combat Efficiency}\left(\frac{\text{Suppression Budget}}{\text{Total Fire Budget}}\right)} \qquad (3)$$

The *Combat Efficiency*, which diminishes with increased fire intensity, determines how effective a given *Suppression Budget* is at decreasing the average *Fire Duration*. Under the condition of no suppression budget, every fire will burn for the *Maximum Fire Duration*, when in reality a theoretical maximum does not exist and a complete lack of suppression forces could lead to some very long-lasting and destructive fires. However, this variable functions more as an average maximum so that the model can provide a high-level, aggregate picture of dynamical outcomes. As mentioned previously, modeling a few severe fires is beyond the scope of this work.

The model assumes a finite *Total Fire Budget* in which resources are divided between suppression and prevention activities. Given the historical tendency of the Portuguese government, and governments from other fire-prone countries, to favor fire exclusion (Aguilar &

Montiel, 2011; “Fire in the west,” 2002; Franklin & Agee, 2003), any increase in suppression expenditures necessarily decreases the amount of resources devoted to prevention. The size of the prevention budget determines the effectiveness with which *Forest Fuel* is drained via *Preventative Removal*, which is modeled as a first order control of the fuel stock. This structure assumes that regardless of the allocation between suppression and prevention, some level of preventative fuel removal will take place. What determines the amount of fuel removed each year is size of the stock of *Forest Fuel* and *Fuel Removal Time Delay*, which is measured in years and can be thought of as a proxy for ease of use. In other words, large fuel removal time delays (e.g. through lack of funds, bureaucratic obstacles, poor planning) result in fewer fuel treatments (e.g. via prescribed burn) per year, while more prevention resources will decrease the delay. This relationship is expressed through the table function in *Table for Effect of Prevention on Fuel Removal* (Figure 17). The function assumes that decreases in the prevention budget relative to the normal results in more severe increases to the fuel removal time delay than does budgetary increases result in decreases to the delay (i.e. the slope is steeper at x<1 than at x>1). Establishment of the maximum and minimum bounds, and general shape, of this function should be improved through further discourse with various experts and field study.

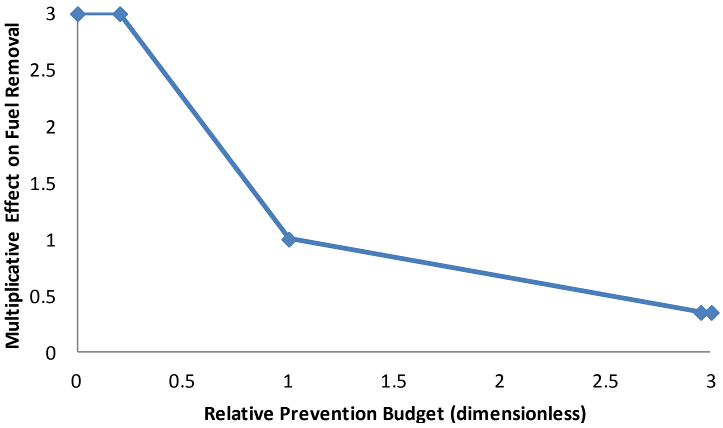


Figure 17. Table function for the effect of relative prevention budget on fuel removal time delay.

The entire SD model, including both the physical and political systems, is displayed in Figure 18.

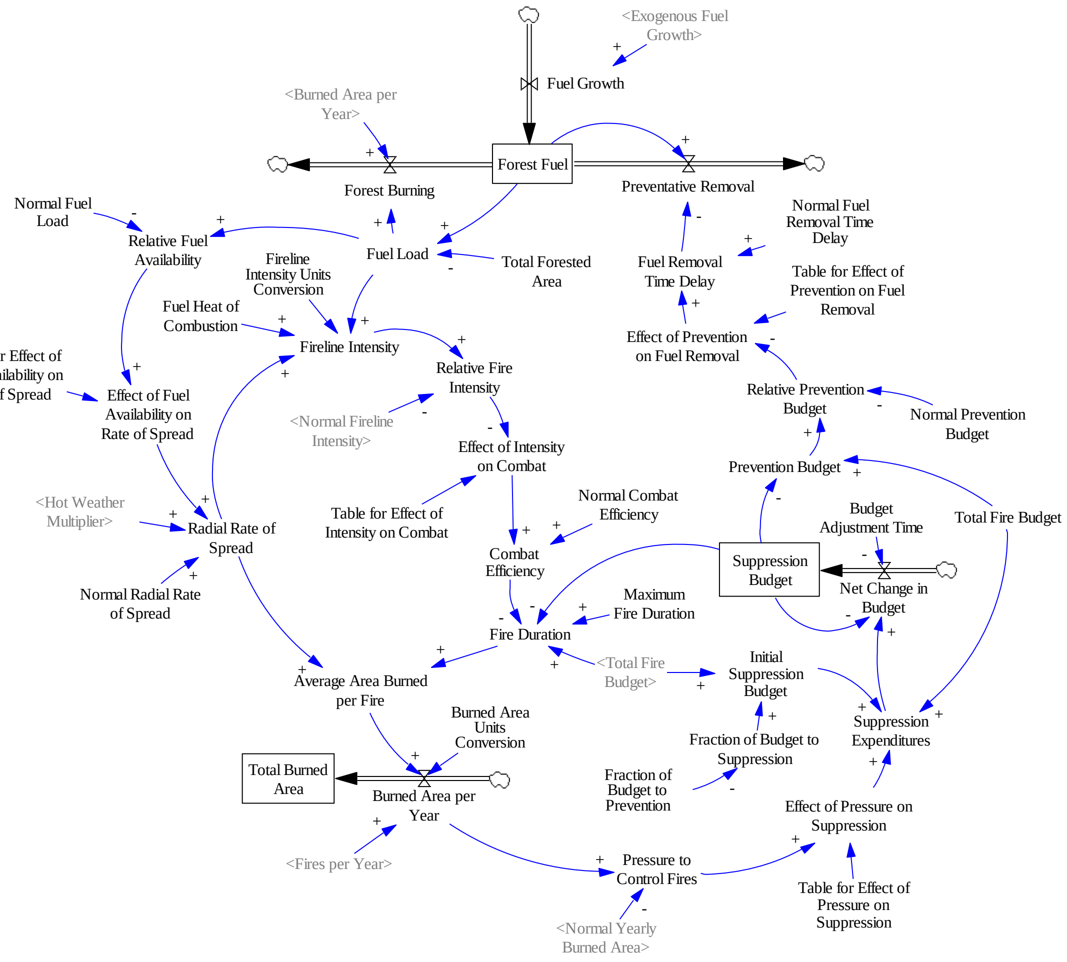


Figure 18. SD model structure of the strategic forest fire management system.

Simulation Initialization and Process

For the case of Portugal, the *Total Forested Area* is set to roughly two-thirds of the natural area, or 6.14 million hectares. *Fires per Year* are assumed constant at the 10-year average in Portugal, or 24,528 occurrences, and the *Total Fire Budget* is €150 million. The standard deviation for the *Hot Weather Multiplier* is 0.08 (a low standard deviation can be used to generate relatively mild weather fluctuations, while a higher one can be used to generate more severe fluctuations).

The simulation time step is one year, and each runs for 150 years. Starting at year 50 there is a 1% increase per year in *Fuel Growth* lasting until year 100. This exogenous ramp increase is a crude portrayal of the afforestation (particularly eucalyptus) and rural abandon that occurred in Portugal starting in the 1950s. Thus, for convenience, one can assume that the 150 year simulation begins in 1900 and runs until 2050, with rural abandon beginning in 1950 and ending in 2000, at which point the fuel growth rate stabilizes at a level roughly 50% greater than where it started. As it stands, the afforestation and rural abandon process is exogenously modeled. Modeling this process endogenously could certainly be valuable. For instance, what are the management implications of further rural abandon? How does it impact the capacity to manage fuel? These are important questions that could be addressed in future work, perhaps by integrating a socioeconomic system with the physical and political systems. Finally, it is worth noting that the purpose of this model is *not* to reproduce historical fire regimes in Portugal, but instead 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.

A separate view in the model is used to establish initial conditions, such that the system begins in equilibrium (Figure 19), and to introduce perturbations into the system, such as pulses, steps, ramps, sine waves, and white noise (Figure 20). In equilibrium (i.e. before afforestation and rural abandon begins), yearly burned area is the 10-year average in Portugal, or approximately 150 thousand hectares. Specifically, *Exogenous Fuel Growth = Normal Yearly Forest Burning + Normal Yearly Preventative Removal*. The notion of equilibrium in a forest ecosystem, let alone any system influenced by humans, may be a bit contrived. In physics, equilibrium is the condition in a system where all competing influences, or forces, are balanced.

In Portugal, with the high variance in yearly ignitions, physically diverse regions, and general uncertainty surrounding human action, the forest system is by definition almost in a constant state of disequilibrium. However, to isolate the impact of relevant socio-physical dynamics on the system, an equilibrium operating mode must be formulated on 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, but it is the *divergences* from equilibrium due both to afforestation/rural abandon and socio-physical dynamics that are central to the analysis of this research, making the initialization of equilibrium less significant.

At the beginning of each simulation, a user can input a fractional (between 0 and 1) allocation of resources to prevention. The balance is dedicated to the suppression budget. With the exception of the allocation, all simulations are run under the exact same conditions. Two are evaluated in Section 4.1 of the results: *Fire Exclusion,* which devotes 60% of initial resources to suppression, and *Focused Prevention*, which devotes 75% of initial resources to prevention. These two allocations do a good job of illustrating relevant socio-physical dynamics, as well as tradeoffs across policies. Allocations 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.

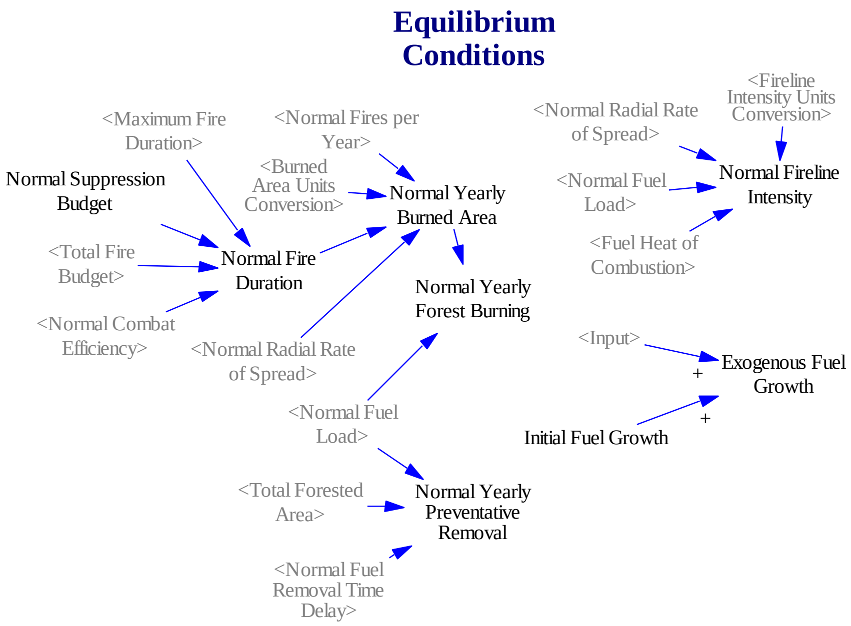


Figure 19. SD model structure used to establish equilibrium operating conditions in the strategic forest fire management system.

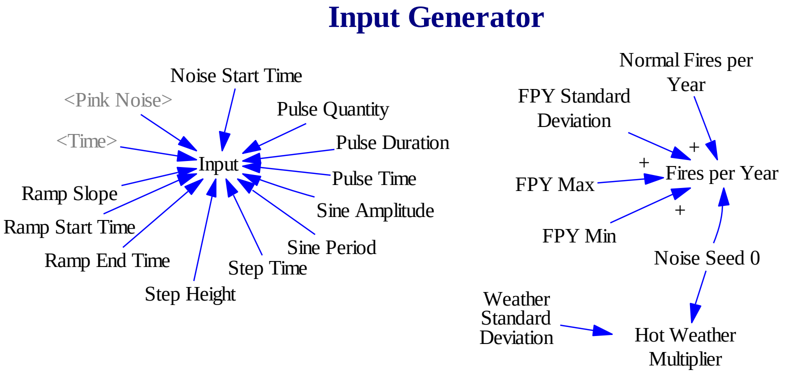


Figure 20. SD model structure for introducing perturbations into the system, adapted from Assignment 1 of 15.872: System Dynamics II at MIT.

3.3.2 Operational SD Model

Forest firefighting operations necessarily include a vast array of different tasks, spanning detection, resource acquisition, deployment, and fire suppression, which are executed by a number of different organizations. Numerous studies, some seminal ones referenced in Section 2.1, have attempted to improve firefighting operations through the optimal allocation of limited resources. Given the time scale and natural representation as a resource-constrained optimization problem (among other factors listed in Table 1), improving firefighting operations through modeling does not seem to cater well to System Dynamics.

In Portugal, however, there is a unique rekindling problem of fires thought to be extinguished. The problem is exacerbated by the high number of ignitions that occur during the summer. As was mentioned in Section 1.1.2, these rekindles represent rework in the operational forest fire management system; in essence they are a *stock* of fires waiting to reignite and enter the system as if they were newly started fires. Thus, while the majority of firefighting operations may be more suitable to optimization or DES approaches, the dynamics of rekindles may be better suited to an SD approach. This is especially true given that the rekindle rate may be a function of organizational pressures.

A simple stock and flow representation of a generalized rework process is shown in Figure 21. Tasks enter and exit the system via the *Task Arrival Rate* and *Task Completion Rate*, respectively. However, a fraction of the *Tasks Awaiting Completion* enters the *Undiscovered Rework* stock via *Tasks Allegedly Completed Requiring Rework*. As the rework is discovered, it reenters *Tasks Awaiting Completion* via *Detection of Required Rework*. If the fraction of tasks requiring rework is large, or if the delays affecting flows in and out of rework are long, then the ability of the system to actually complete tasks can become severely undermined.

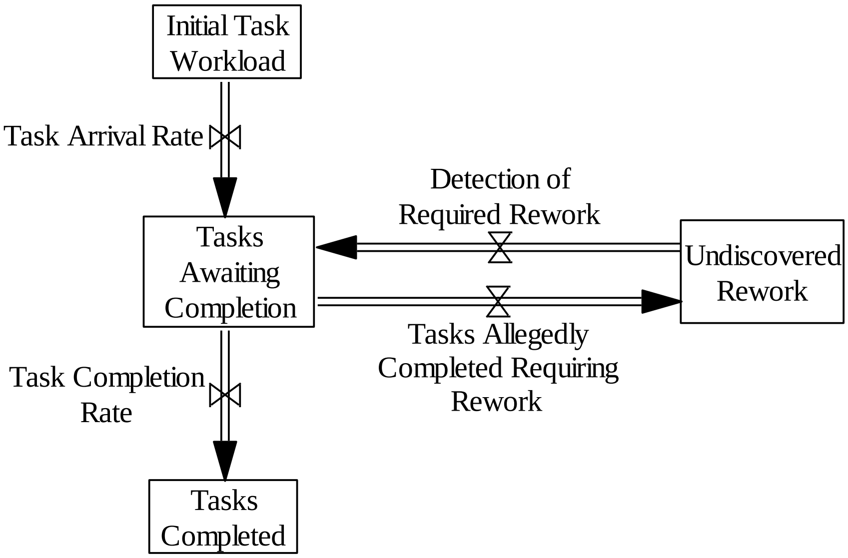


Figure 21. A generalized rework process modeled with stocks and flows.

The analogy of this process to forest fire management is through insufficiently extinguished fires that later rekindle, though this process can be generalized to a number of other systems, such as the IT call center from Section 3.2.2 or new product development (Repenning, 2001). Rework itself is not a bad thing; improvement of overall system performance often requires some amount of rework. But, when the system becomes inundated with rework the ability to actually complete tasks is compromised, which may detract from other activities or simply collapse the system. What causes spikes in rework varies from system to system, but with regard to rekindles it is hypothesized that aggressive suppression time targets, at least in part, contribute to the problem. This unintended consequence of a seemingly beneficial policy is demonstrative of the “Fixes the Fail” archetype, and the remainder of this section will detail the model structure that leads to this archetypal behavior.

The Operational SD Model Explained

The operational forest fire management system (Figure 22) incorporates relevant dynamics with the rework structure into a simple model that tracks fire activity over time. While the strategic model (Section 3.3.1) develops dynamics over many years, this model focuses on relationships affecting firefighting operations during the fire season, specifically fire suppression. As such, the time horizon is much shorter, with rates occurring per day instead of per year.

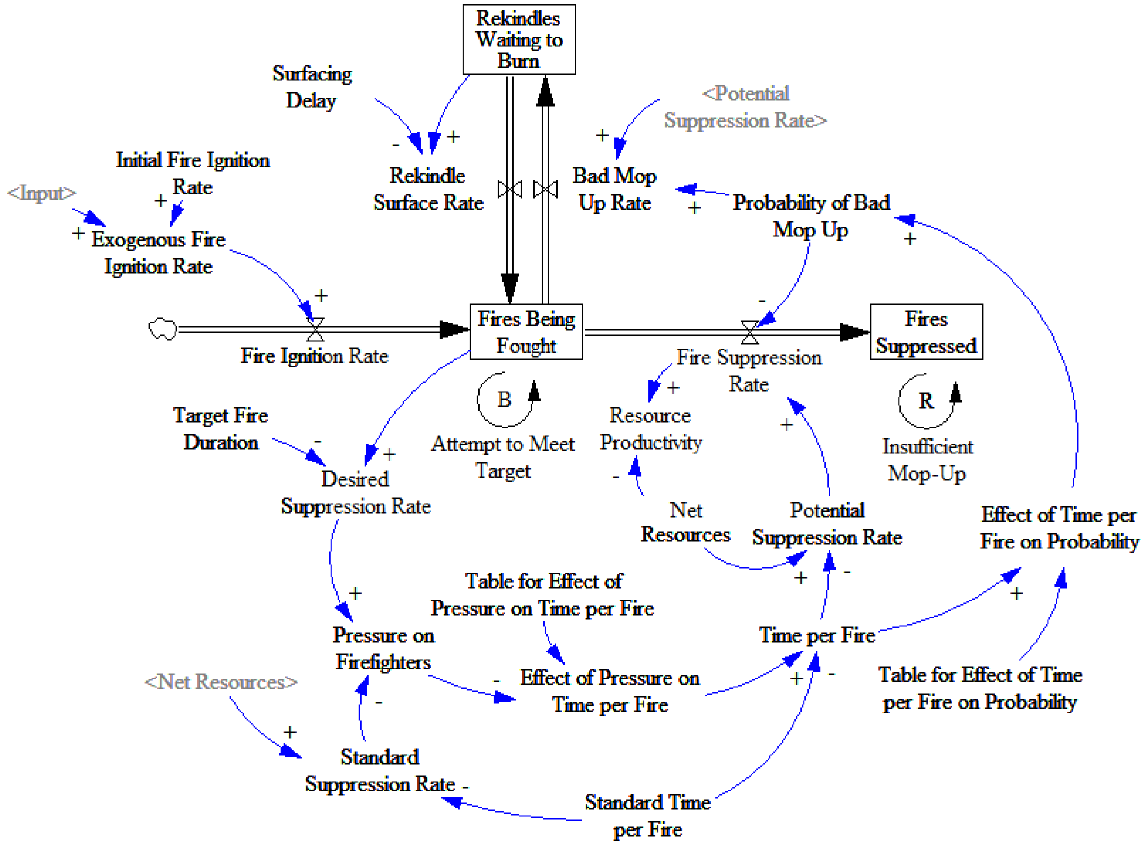


Figure 22. SD model structure of the operational forest fire management system.

Fires enter the suppression system according to the *Fire Ignition Rate*, which is initialized to a constant daily rate, but may fluctuate according to the *Input* function. The *Input* function can be used to generate pulses, steps, ramps, and sine waves similarly to the one in the strategic model (Figure 20). *Fires Being Fought* is the stock of fires in the system, and they exit according to the *Fire Suppression Rate*. What determines this rate depends on a variety of interacting variables.

Target Fire Duration is a surrogate for the 90-minute suppression target employed by fire managers in Portugal. It represents the goal of fire suppression organizations to extinguish fires quickly such that they can respond to new fires. The actual duration used in the model is not 90 minutes; in fact very little of this model is parameterized to real world conditions in Portugal. The reason for this is straightforward, but oftentimes hard for managers to grasp. As Table 1 indicates, the purpose of System Dynamics is not to closely model system behavior or replicate past performance, which requires statistically valid parameters. Instead, SD models provide holistic pictures of the feedbacks affecting system behavior over time. In what magnitude SD models often cannot say, but the mere presence of feedbacks, particularly ones that undermine system performance, is valuable information to managers of complex systems. Nonetheless, some managers are accustomed to the "free" black-box solutions of highly mechanized decision support systems, and are less willing to engage the insights of SD simulations since a clear solution often doesn't exist. What these managers fail to realize is that simply starting a conversation about potential negative feedbacks and challenging standard operating procedures may spark systemic change, or at the very least motivate data collection to evaluate the supposed impact of such feedbacks. Regardless, this discourse should make it clear that both the strategic and operational models are ultimately toy models, serving more of an educational rather than prescriptive role.

The fire suppression target in essence creates a *Desired Suppression Rate*, equal to the quotient of *Fires Being Fought* and *Target Fire Duration*. *Pressure on Firefighters* is a dimensionless variable equal to the quotient of *Desired Suppression Rate* and *Standard Suppression Rate*. The standard rate is assumed to be an equilibrium operating rate (i.e. where fires into the system equal fires out of the system, and there are no rekindles; specifically *Fire Ignition Rate* = *Fire Suppression Rate* and *Bad Mop Up Rate* = *Rekindle Surface Rate* = 0), and as the desired rate increases over this baseline, pressure accumulates and the *Time per Fire* decreases according to *Table for Effect of Pressure on Time per Fire* (Figure 23). The function assumes that pressure has a diminishing effect on the time spent per fire (measured in resource-days per fire) as pressure grows, eventually approaching a theoretical minimum.

Figure 23. Table function for the effect of firefighting pressure on time per fire.

The variables *Target Fire Duration* and *Time per Fire* sound similar but stand for different things. While *Target Fire Duration* is a time target, *Time per Fire* is basically the amount of man-hours spent on each fire (the model uses resource-days instead of man-hours but the concept is the same). Given some number of *Net Resources* available in the system, the *Standard Time per Fire* is initialized such that the standard suppression rate equals the desired one (i.e. equilibrium operating conditions). Thus, divergences from the standard number of resource-days per fire are driven solely by increases in the *Fire Ignition Rate*, such as the late summer ignition spikes characteristic of Porto district (Figure 4).

The first order effect of more pressure is that firefighters expend fewer man-hours per fire, which, assuming the fires are actually extinguished (or at least appear to be extinguished) results in a higher suppression rate. This balancing loop is titled *Attempt to Meet Target* and is analogous to firefighters relying on aircraft-based tactics instead of time-consuming groundwork. However, as *Time per Fire* becomes increasingly smaller, the *Probability of Bad Mop Up* increases according to the *Table for Effect of Time per Fire on Probability* (Figure 24). This casual logic is by no means farfetched. As firefighters devote less and less time to each fire (driven ultimately by the pressure to extinguish fires in 90 minutes or less), they rely more and more on easy, quick-fix solutions. In Portugal, this often means using airborne water technology such as water drops. As the number of man-hours per fire decreases, the probability that a mistake is made or a problem is overlooked increases.

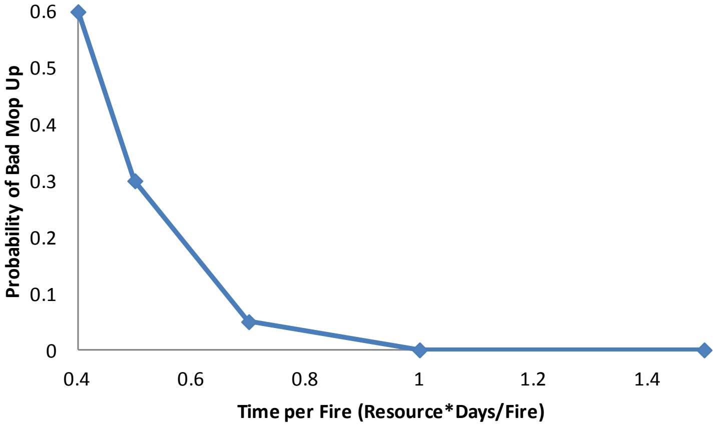


Figure 24. Table function for the effect of time per fire on probability of bad mop up.

As was discussed in Section 1.1.2, the problem in Portugal, particularly the northern districts, is that fires are insufficiently mopped up after allegedly being extinguished. Mop up work is time-consuming and laborious, requiring hand tools around the entire fire perimeter, but without it fires are allowed to smolder underground. If these fires reach a root network, then they can propagate to the surface and rekindle. The rate at which fires become rekindles is the *Bad Mop Up Rate*, equal to the product of the *Potential Suppression Rate* and *Probability of Bad Mop Up*. Conversely, the *Fire Suppression Rate* is equal to the product of the *Potential Suppression Rate* and the complement of the *Probability of Bad Mop Up*. The probability is really more like a fraction; as that fraction goes up more (insufficiently) extinguished fires become rekindles and fewer are actually suppressed. Thus, as the number of fires being fought increases, particularly if it's a large and sudden increase, the reinforcing loop titled *Insufficient*

Mop-Up may overcome the balancing effect of less time spent per fire, which results in a lower suppression rate and ultimately more fires in the system.

The *Resource Productivity* variable (defined as the quotient of *Fire Suppression Rate* and *Net Resources*) calculates how many fires per day each resource is actually suppressing. If the rekindle rate is high, then the productivity will decrease as more fires enter the rework process instead of being fully suppressed. In general, higher resource productivities are favorable in fire intervention organizations.

Simulation Initialization and Process

The *Initial Fire Ignition Rate* is set to 20 fires per day. This rate should be interpreted as an average or normal condition for a given region in Portugal, but its selection is ultimately arbitrary since the rest of the parameters in the model are chosen such that this represents the equilibrium input into the system. *Net Resources* is initialized to 20 resources and *Standard Time per Fire* to one resource-day per fire such that the *Standard Suppression Rate* is equal to 20 fires per day. Absent any perturbations to the system, the standard rate will equal the potential rate, which will equal the *Fire Suppression Rate*. And, if the *Fire Suppression Rate* equals the *Fire Ignition Rate*, the system will remain in equilibrium.

Each simulation lasts for 92 days (the length of Charlie Phase) and the time step is one day. The purpose of the simulations in the operational model is to examine system behavior under different scenarios of sudden, intense fire activity, such as the spikes that occurred in Porto in 2010 (Figure 4). These spikes are what can cause the fire response system to collapse as resources are drawn thin and crews are redeployed to fire sites previously thought to be extinguished. Using the *Input* function, pulses of 70%, 90%, and 100% are introduced on the 40th day, each lasting for ten days before dropping back down to the equilibrium ignition rate. These three scenarios do a good job of illustrating relevant socio-physical dynamics; results from them are presented in Section 4.2.

The operational model is sufficiently simple in that it seeks only to model the rework dynamics stemming from rekindles and organizational pressures. The literature on organizational dynamics indicates that there are many other potential feedback loops affecting the performance of organizations, applicable as well to forest firefighting institutions. These include the dynamic impacts of working overtime, fatigue or burnout (particularly relevant in forest firefighting in Portugal), and hiring/firing, among others. While these dynamics could be incorporated into future more sophisticated models, the current model structure allows the user to observe how some relevant and important socio-physical dynamics affect the incidence of rekindles, a major problem in Portugal.

Chapter 4. Results

In this section simulation results are presented for the strategic and operational models. A select number of simulations are chosen to illustrate the aforementioned socio-physical dynamics driving system behavior in the two systems without cluttering the output graphs. By building and then quantifying the impacts of these dynamics in a simulation model, this research achieves its first objective (refer back to Section 1.2). 0 discusses the results in light of their implications on policy and management and Chapter 6 makes informed recommendations, thus achieving the second objective. The following section presents results from the strategic model.

4.1 Outcomes from the Strategic Model

The results explain the outcomes of the two policies, fire exclusion (60% of initial resources to suppression) and focused prevention (75% of initial resources to prevention), by tracking variables over time that interact with each other via the three major feedback loops of Figure 11, starting with the *Fire Control* loop below. While fire exclusion confers short-term benefit in terms of shorter fire durations and less burned area at first, focused prevention results in less total burned area in the long-run. The reason being that, after the onset of afforestation and rural abandon, fire exclusion produces overwhelmingly negative feedback effects that trap the system in a worse state in the long-run.

4.1.1 Fire Control Loop

First, it is useful to see the graphical portrayal of afforestation and rural abandon (Figure 25), which was crudely characterized by an exogenous ramp increase to fuel growth (note that this is a rough analog to Figure 3).

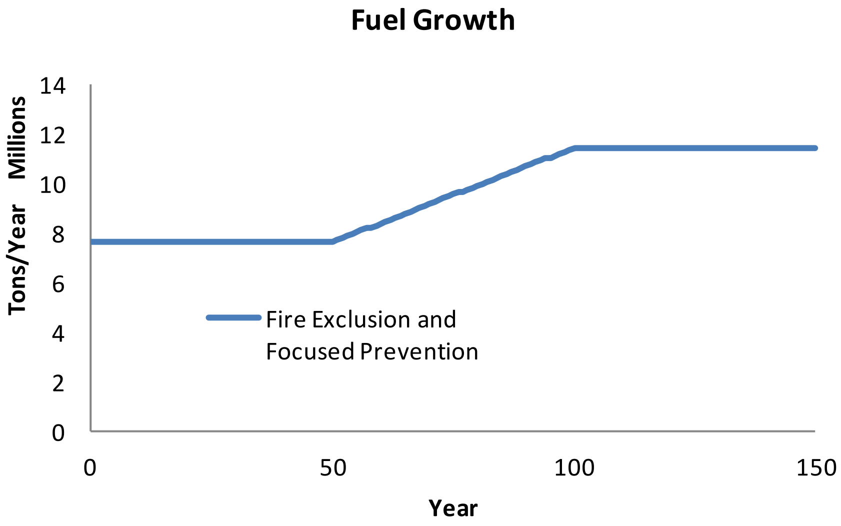


Figure 25. Exogenous representation of afforestation and rural abandon in Portugal through ramp increase to fuel growth.

Figure 26 displays the percent of the total fire budget being used for suppression by the two management scenarios over time. Under fire exclusion, the suppression budget eventually approaches the total budget. If the objective is to protect people and property near the forest, such a pronounced increase is not necessarily a bad thing given that more suppression resources results in shorter fire durations (Figure 27). And, shorter fire durations lead to less burned area per year, which is the goal of fire exclusion policy as stated in the literature. This is the *intended* consequence of increased fire suppression and the *Fire Control* loop in general. On the contrary, focused prevention leads to suppression expenditures that fluctuate, but are relatively stable around 40% of the total fire budget. And thus, fire durations are longer.

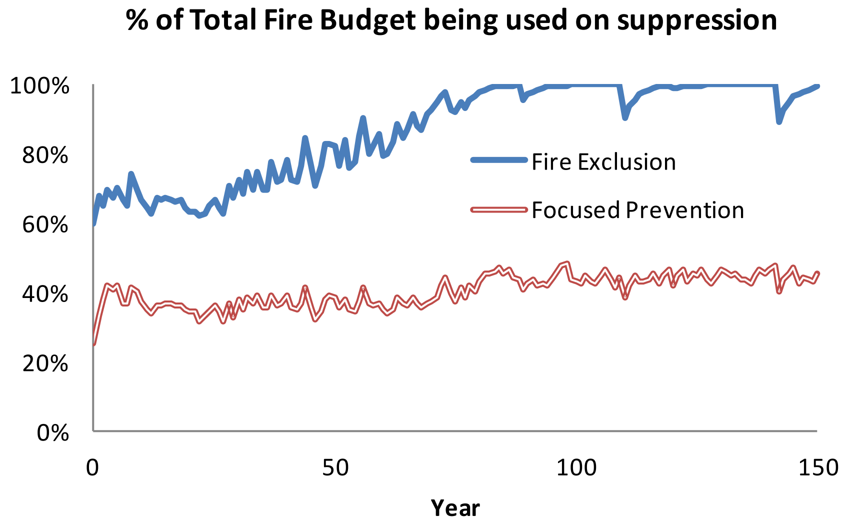


Figure 26. Under fire exclusion, the entire fire budget is eventually dedicated to suppression.

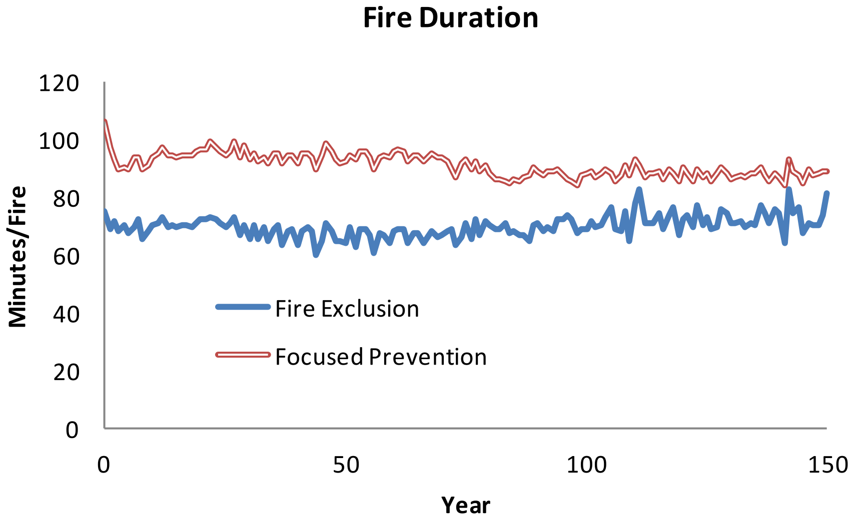


Figure 27. Fire durations are shorter under fire exclusion, the intended effect of more fire suppression.

4.1.2 Prevention Resource Scarcity Loop

Figure 28 displays relative fireline intensity, which increases dramatically under fire exclusion. This factor decreases the ability of suppression forces to effectively control fires via reduction in the combat efficiency, which in turn leads to longer fires. Thus, if not for the increases in intensity, the fire durations under fire exclusion would be even shorter. Furthermore, the rate of spread of each fire under fire exclusion increases beyond that of focused prevention (Figure 29).

Together, fireline intensity and rate of spread comprise the *Fire Severity* measure of Figure 11, which increases as fuel accumulates. Figure 30 displays fuel load under each management scenario. Afforestation and rural abandon drive a substantial part of the fuel load increase; however, both policies experience this exogenous increase equally and yet fuel load is much higher under fire exclusion. What is causing this outcome?

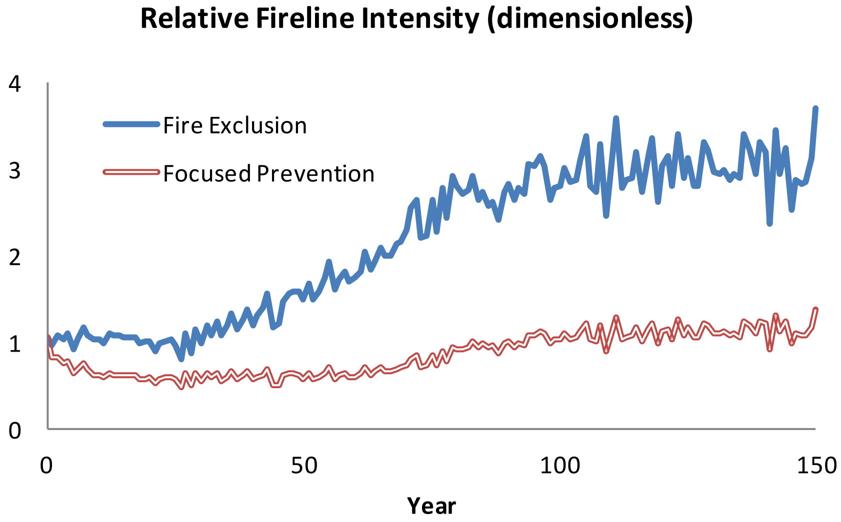


Figure 28. Fires become more intense over time under fire exclusion due to fuel load increases.

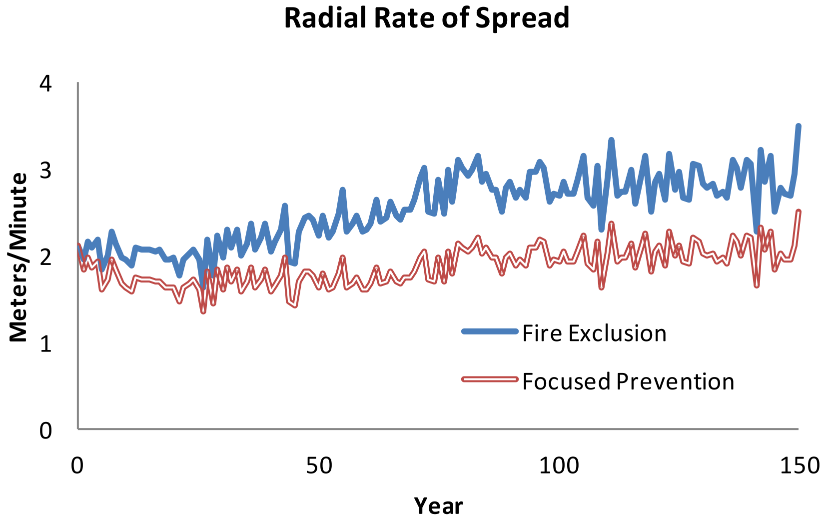


Figure 29. Fires burn faster over time under fire exclusion also due to fuel load increases.

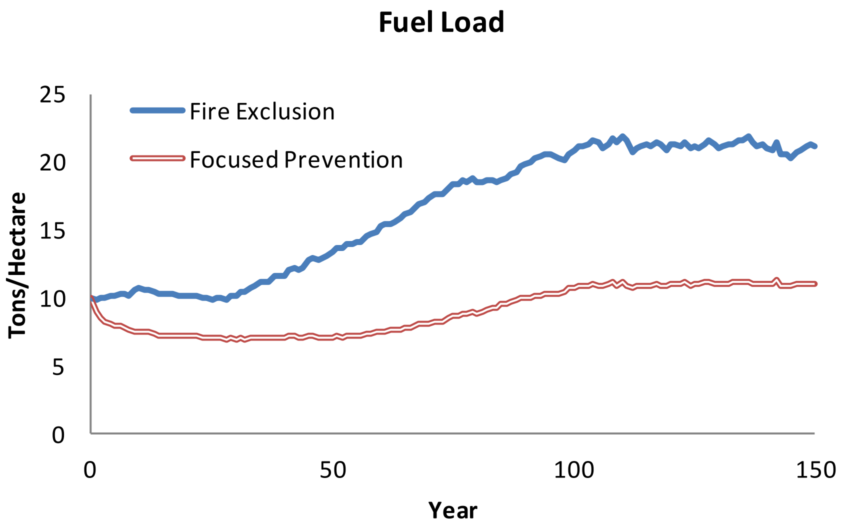


Figure 30. Fuel load grows larger under fire exclusion due to exogenous increase, and also system feedback.

The primary reason for the discrepancy is the difference in yearly preventative fuel removal (Figure 31). Fuel removal under the two policies is comparable for a while but diverges considerably after afforestation and rural abandon run their course. If the finite budget assumption is valid, then this result makes sense. When competing for finite resources in a government budget, increases in one area will necessarily decrease resources in another. This dynamic is straightforward given just two potential allocations of government resources. Thus, not surprisingly preventative removal is lower under fire exclusion since over time suppression dominates the budget (Figure 26). As preventative fuel removal declines, the stock of fuel increases, which leads to increases in fireline intensity (and subsequent decreases to combat efficiency) and rate of spread. The combination of these factors translates to more burned area and further pressure to control fires with more suppression forces. Thus, increased suppression expenditure reinforces further expenditure, and the *Fire Control* loop has an *unintended*, positive effect on the fuel stock.

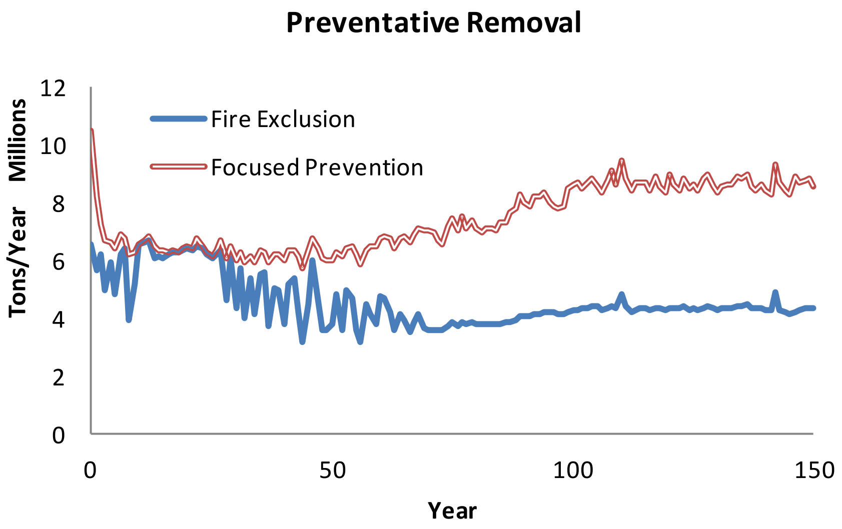


Figure 31. With a finite budget, excessive suppression expenditure under fire exclusion undermines preventative removal.

One of the major drivers of preventative removal is the fuel removal time delay. Figure 32 displays this delay. Note that the delay under focused prevention policy is substantially lower than the delay under fire exclusion policy. The discrepancy in delays is largely a result of the shape of the table function describing the relationship between relative prevention budget and the fuel removal delay (Figure 17). The results are very sensitive to this function and should thus be interpreted within the uncertainty of this function's shape. As previously stated, improving the shape of this function through further discussion with experts, as well as extended field observation of forest owners and managers who actually conduct fuel management in Portugal, would be valuable future work.

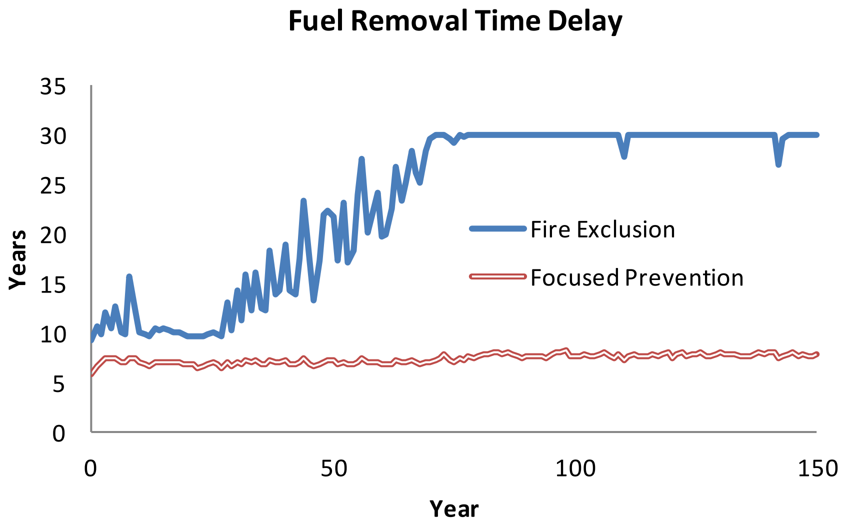


Figure 32. The ease with which preventative treatments are conducted diminishes rapidly under fire exclusion.

4.1.3 Native Fire Regime Loop

Preventative fuel removal decreases the fuel stock, but so too does forest burning due to natural, human-caused, or accidental fires. While these fires may be destructive to property and ecosystems, they produce a natural balancing effect on fuel load across the affected landscape. Thus, in theory the fuel stock should decline with increased forest burning. Figure 33 displays forest (fuel) burning for the two policies, which increases substantially under fire exclusion. Despite experiencing more forest burning (which decreases the fuel stock), fire exclusion nonetheless maintains larger fuel loads than focused prevention over time (Figure 30). 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 that are set into motion by afforestation and rural abandon.

Figure 34 captures the amalgamation of these dynamics on the five-year moving average of burned area per year. Fire exclusion leads to smaller burned area at first, but after the onset of afforestation and rural abandon, burned area per year surpasses focused prevention and becomes more volatile. This result is consistent with the claim that large and severe fire seasons are a modern artifact of dedicated fire suppression policy (Minnich, 1983, 2001; Minnich & Chou, 1997). Focused prevention, by comparison, produces a much less volatile stream of burned areas over the course of the simulation. It is worth noting that the pressure to control fires variable (from Figure 11), which drives suppression expenditure, has the same graphical progression as Figure 34 but is scaled accordingly.

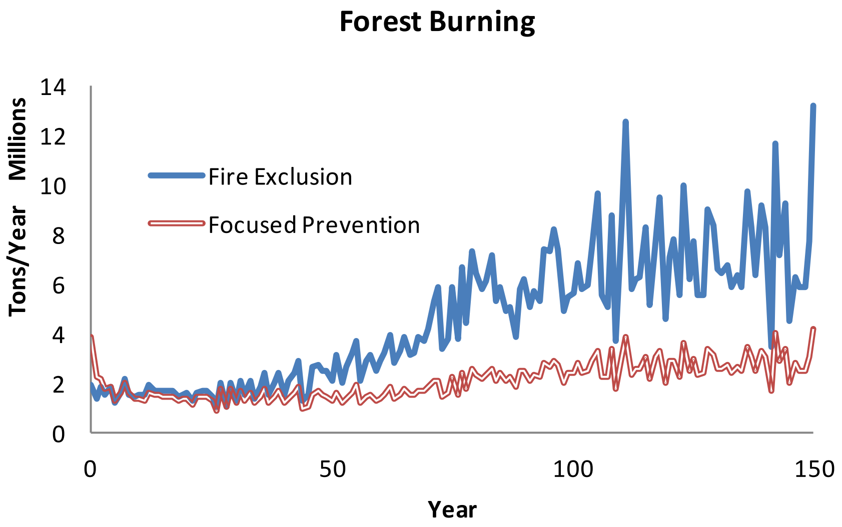


Figure 33. Forest burning under fire exclusion increases over time, yet the fuel stock remains high.

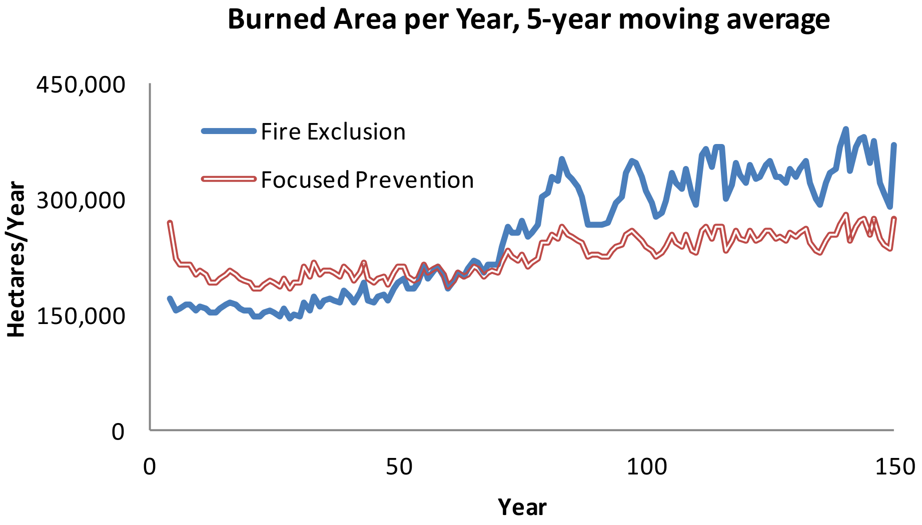


Figure 34. Burned area per year is mild at first under fire exclusion, but in the long-run becomes more severe and volatile.

Total burned area (Figure 35) is a straightforward metric for evaluating management allocations against one another because it represents the accumulation of burned area, a proxy for total costs, over the course of the simulation. An attractive policy should minimize these costs. Fire exclusion appears to be the better policy until approximately year 105, when its total burned area surpasses focused prevention. This occurs because around year 75 the reinforcing loops seeking to increase burned area start to overcome the balancing loops seeking to decrease it, resulting in an increase in the rate at which the area burns (the slope, or derivative, of the curve in Figure 35 is burned area per year, i.e. Figure 34). Because burned area continues to get worse under fire exclusion, suppression expenditure remains at the maximum, perpetually undermining preventative fuel removal and thus keeping fuel loads high, which is ultimately the underlying cause of severe fire activity.

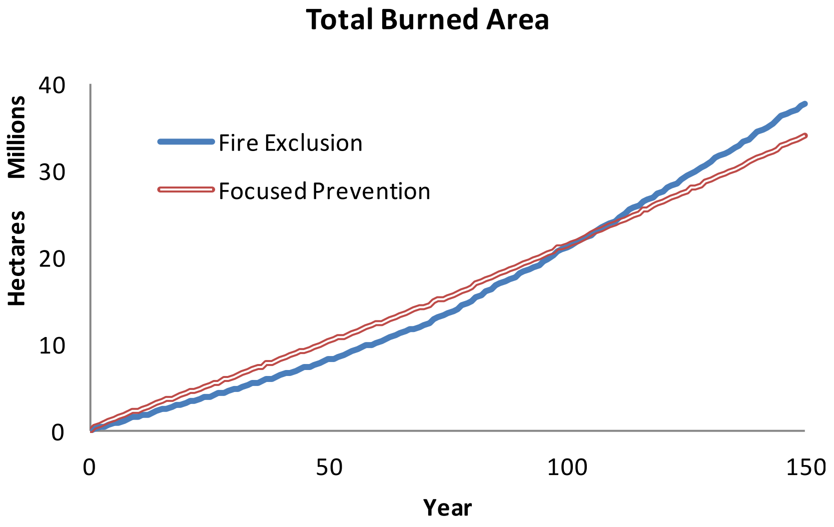


Figure 35. Total burned area under fire exclusion, while smaller initially, in time surpasses focused prevention.

While excessive suppression expenditure has adverse long-term consequences, so too does excessive prevention expenditure. Figure 36 displays a five-year moving average of burned area per year for three management allocations. The first allocates 40% of initial resources to suppression; based on the parameterization of the model, this allocation results in a (near) minimal amount of total burned area at the end of the simulation. The second allocates 90% of initial resources to suppression, and the third allocates 90% of initial resources to prevention. The figure shows that while too much suppression may be a bad thing, an insufficient amount can also be detrimental as fires on average burn longer. Too few suppression resources would likely also result in further damages to property and lives lost, further exacerbating costs. The purpose of Figure 36 is to convey that a balance of suppression and prevention activities is clearly optimal. The exact allocation itself is not meaningful (40% to suppression happened to be the best option), but the idea that a balance of suppression and prevention minimizes total burned area is both realistic and further justified in light of the socio-physical dynamics impacting management over time.

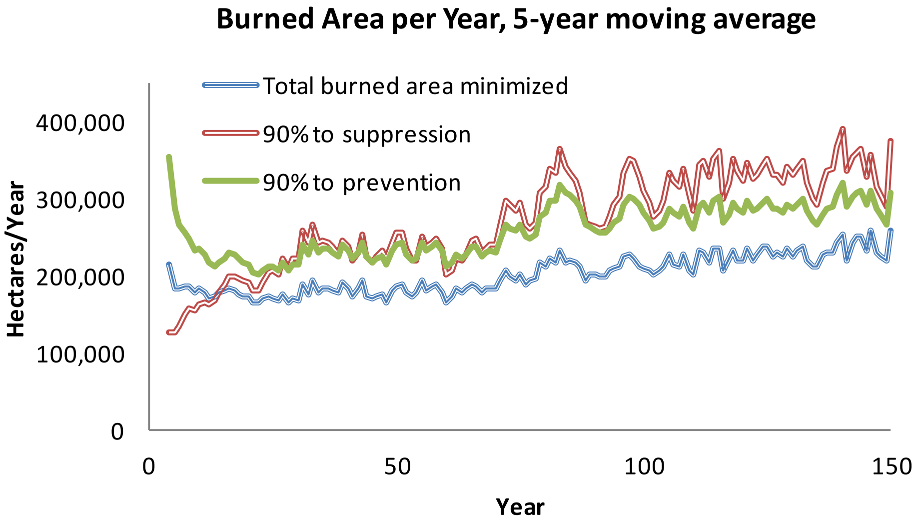


Figure 36. A balance of suppression and prevention resources that minimizes total burned area is optimal.

The following section presents results from the operational model of forest fire management.

4.2 Outcomes from the Operational Model

The operational model seeks to quantify the impacts of sudden ignition spikes on rekindle activity and fire suppression productivity. Results are presented across three different ignition spikes, 70%, 90%, and 100%, both starting on day 40 and lasting for ten days. Similarly to Section 4.1, the results are explained through discussion of the two feedback loops portrayed in Figure 22, starting first with the *Attempt to Meet Target* loop. Results show that under mild ignition spikes, the system can effectively manage the influx of additional fires. However, more severe spikes lead to perpetual rework in the form of rekindled fires, which trap the system in a worse state in the long-run.

4.2.1 Attempt to Meet Target Loop

First, it is useful to see a graph of the three different ignition spikes, a 70%, 90%, and 100% 10-day pulse (Figure 37).

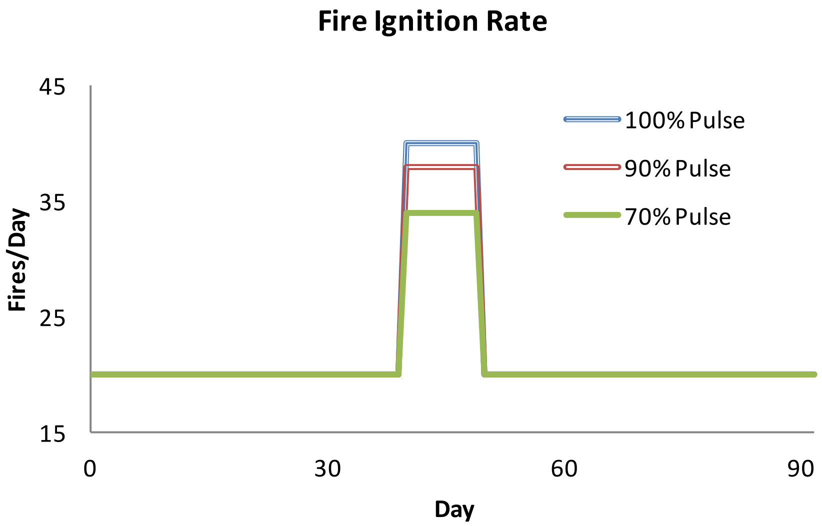


Figure 37. 10-day pulses of 100%, 90%, and 70% over the equilibrium fire ignition rate are introduced into the system.

As the number of fires entering the system increases, pressure mounts on firefighting crews to extinguish fires faster. The target fire duration is equivalent across the three scenarios, so pressure is proportional to the size of the ignition spike, but as Figure 38 shows, this relationship is highly nonlinear. Under the 70% pulse, pressure reaches a small peak, but then normalizes rather quickly. Under the 90% pulse, pressure reaches a moderate peak and normalizes more slowly, while under the 100% pulse pressure reaches a higher state and stays there until the end of the simulation. The difference in behavior between the 90% and 100% pulses is quite profound despite the mere ten percentage point difference.

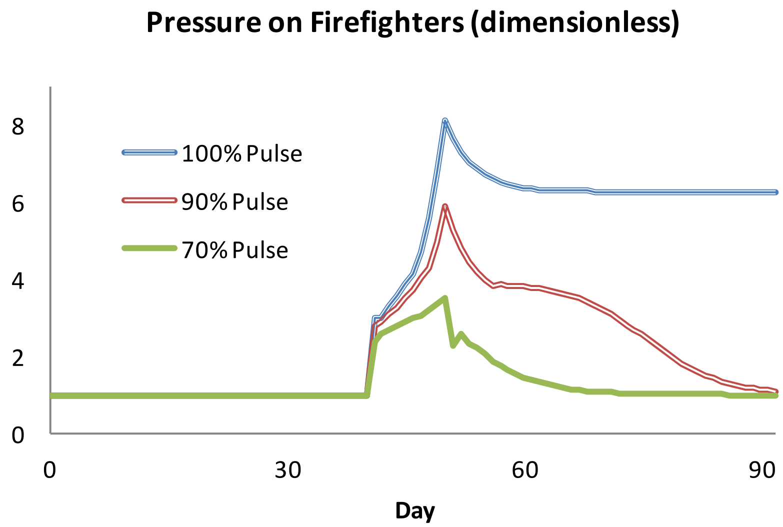


Figure 38. Pressure on firefighters normalizes under the 70% and 90% pulses, but not under the 100% pulse.

According to the model logic, as pressure increases the time spent per fire in terms of resource-days per fire decreases according to a nonlinear table function. As in the strategic model, much of the system behavior in the operational model is sensitive to the shapes, or curvature, of the table functions. The function curvature relating pressure with time per fire has not been characterized in Portuguese intervention and response teams, nor has it been documented in the forest fire management literature. However, if the *general* curvature of the function is realistic to fire managers, then future work could collect relevant data to better quantify it (much like the relationship between prevention resources and fuel removal time delay in Figure 17; this is discussed further in Appendix E: Rekindle Mitigation Project). Nonetheless, both the 70% and 90% pulses result in decreased times per fire that eventually normalize, while the 100% pulse reaches a new minimum at 0.4 resource-days per fire (Figure 39).

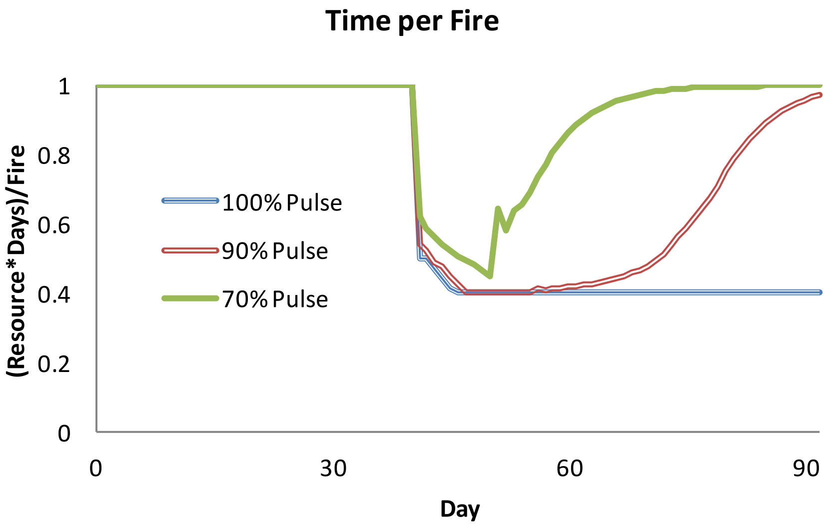


Figure 39. The amount of manpower devoted to each fire permanently decreases due to the 100% pulse.

Given that net resources are equivalent across the three scenarios, the potential suppression rate changes solely with the time per fire (Figure 39 and Figure 40 are mirror images over some horizontal, though the units are different). What Figure 40 says is that as pressure increases and fewer man-hours are spent per fire, it is *possible* to suppress a larger number of fires. This is the essence of the balancing *Attempt to Meet Target* loop; as more fires enter the system, crews spend less time on each fire (perhaps by calling in a water drop but not following up with necessary groundwork/mop-up) and thus would appear to be able to extinguish more fires as a result. This is clearly not the whole story, the remainder of which is discussed in the next section.

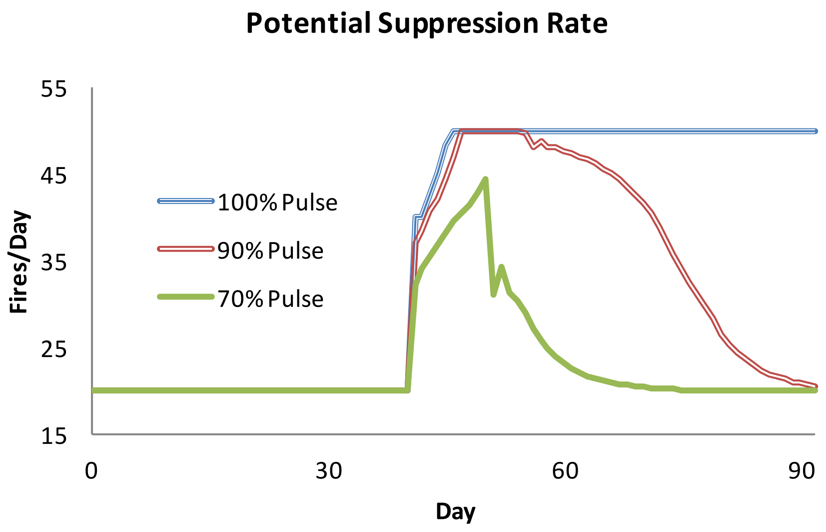


Figure 40. The potential suppression rate under the 100% pulse increases due to less time spent per fire, but that does not mean all of the fires are necessarily suppressed.

4.2.2 Insufficient Mop-Up Loop

The unintended consequence of fewer man-hours per fire is that the probability of insufficient mop-up increases, as shown in Figure 41. The extent to which this probability increases is difficult to quantify, but the logic governing the increase is sound. As crews feel the pressure to extinguish fires in 90 minutes or less, they cut corners and leave fires prematurely in order to respond to new fires. The higher likelihood of insufficient mop-up means the bad mop up rate will increase and more of the fires in the system will become rekindles waiting to burn. In fact, Pacheco (2011) showed through an analysis of fire "genealogies" that fires can, and often do, rekindle more than once. Figure 42 shows how under the 100% pulse, there is a permanent number of rekindles in the system while all of the rekindles under the 70% and 90% pulses are eventually suppressed.

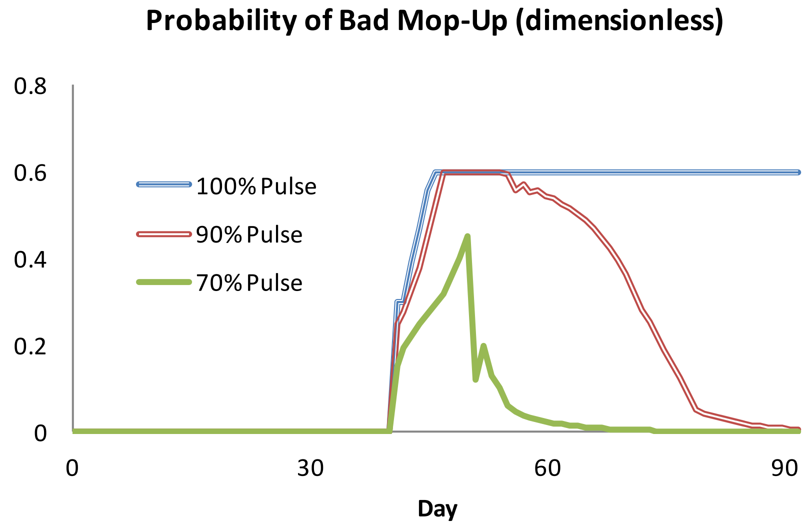


Figure 41. The probability of bad mop up increases due to the ignition spikes, but it stays non-zero under the 100% pulse.

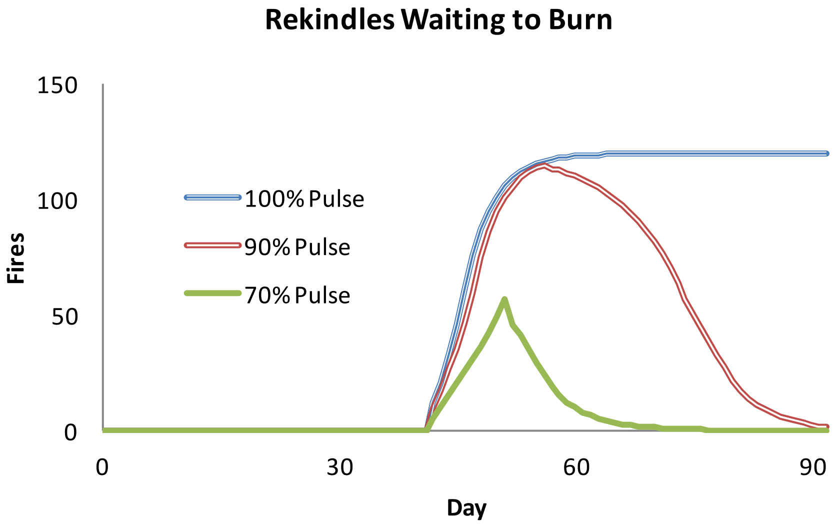


Figure 42. There are a permanent, or steady-state, number of rekindles in the system under the 100% pulse.

With a permanent number of rekindles in the system, pressure stays high for the firefighting crews, which means time per fire stays low and the fraction of insufficiently mopped up fires also stays high. This reinforcing effect is the essence of the *Insufficient Mop-Up* loop, and it shows that if the ignition pulse into the system is large enough, then the system may become trapped in a worse state in the long-run due to these feedbacks. Figure 43 is another way of seeing this behavior. While the 70% and 90% pulses of ignitions are eventually dealt with and the equilibrium number of fires in the system is restored, the 100% pulse leads to a *new* equilibrium where the number of fires in the system is much higher. Indeed, even if the simulation time is extended greatly, the number of fires in the system never drops below the new equilibrium of approximately 63 fires (20 in the old equilibrium).

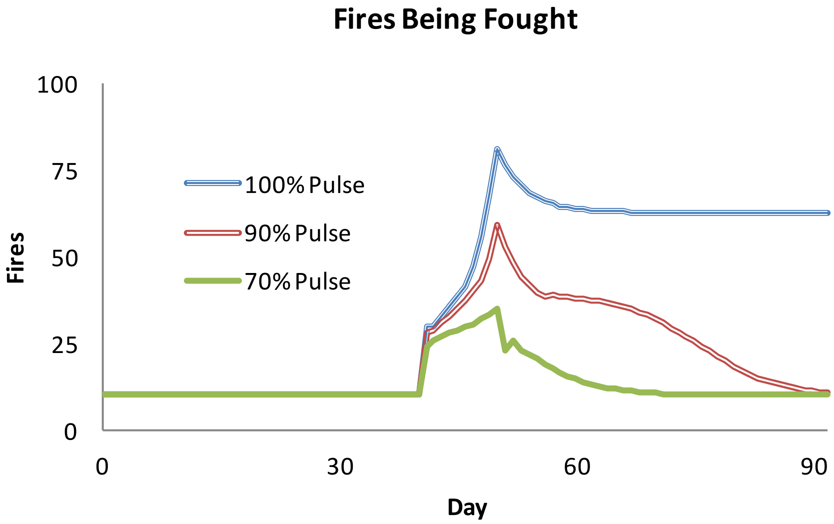


Figure 43. The system gets trapped in a worse, long-run state of more fires after the 100% pulse.

The idea of a new equilibrium number of fires in the system is of course an artificial construct; in reality all of the fires from the 100% pulse would eventually become extinguished, but likely with much greater consequence than the other pulses given the large number of rekindles that stay locked in the system for some time. Nonetheless, it is worth noting that due to the rekindle rework process, fewer fires are actually suppressed under the 100% pulse compared to other pulses at the end of the simulation. Approximately 2,017 fires are extinguished in the 90% pulse scenario, 1,980 in the 70% scenario, but only 1,867 in the 100% scenario. To reiterate, the numbers themselves are not meaningful, but the general takeaway is that despite more fires entering the system under the 100% pulse, fewer ultimately leave.

One of the findings from this simple model is that the target fire duration (whether its 90 minutes or more or less) has a significant effect on the system dynamics. Consider a situation where the target fire duration is doubled. Such a rule may at first outrage the public and seem unproductive or counterintuitive by fire managers. However, as Figure 44 shows, the longer target fire duration actually allows the system to return to the pre-ignition pulse equilibrium (though this is higher than the pre-ignition pulse equilibrium under the shorter target fire duration). The peak number of fires in the system is higher under the larger target fire duration, and this result makes sense. Crews are spending more time managing fires, presumably conducting sufficient mop-up, and thus more fires are burning at any one time. However, because these fires are being managed more comprehensively (i.e. lower probability of bad mop-up), the system does not get trapped in the perpetual rework process as it does under the shorter target fire duration where the system stabilizes to a much larger equilibrium number of fires.

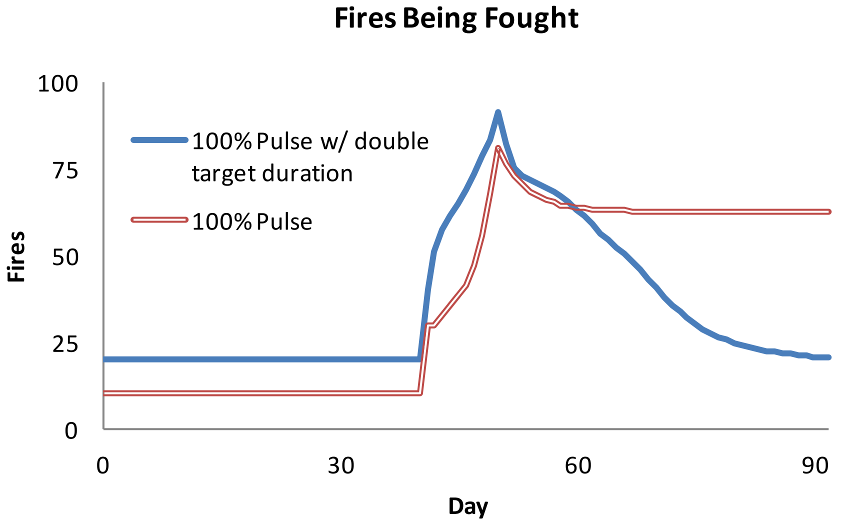


Figure 44. A longer target fire duration allows the system to stabilize under the 100% pulse.

The following chapter discusses the results from the strategic and operational models, including implications and limitations.

Chapter 5. Discussion

There are some common themes from the results of the strategic and operational models despite addressing different problems on very different time scales. Section 5.1 will discuss these themes, including policy resistance, the firefighting trap, and tradeoffs between short- and long-term gain. This section will also discuss the general impacts of technology on policy decisions in forest fire management. Section 5.2 will discuss limitations of the models and how they might impact the validity of the results.

5.1 Policy Implications

The strategic and operational models dealt with two different problems in forest fire management in Portugal, yet they were similar in that the interactions between human decision making (social systems) and forest response (physical systems) were integral to the consequences of the problem over time. As was mentioned in Section 2.2, most System Dynamics models are similar in that they try to demonstrate the side effects or unintended consequences of seemingly rational policies, the so-called policy resistance of systems. In the strategic model, a seemingly logical decision in light of increased fire damages is to increase suppression capacity. With more resources dedicated to fire suppression, damages from fire should be reduced. In the operational model, a seemingly logical decision in light of intense summer fire activity is to try and decrease time spent at each fire in order to respond to more of them. With less time spent at each fire, which is possible given advances in airborne water technology, more fires can be suppressed. In both models, these decisions may appear sufficient at first, or under mild circumstances, but over time the socio-physical dynamics produce unintended consequences. In the strategic model, increased suppression expenditures undermine preventative fuel removal, leading to excess fuel accumulation and more severe fire seasons in the future. In the operational model, spending increasingly less time on each fire results in insufficient mop-up, which leads to rekindles that further stress firefighting capacity. Both demonstrate two distinct aspects of policy resistance that manifest in forest fire management in Portugal.

Both models go beyond policy resistance and show that adherence to the seemingly correct, though inferior, decisions can *trap* the system in self-reinforcing feedback loops of inferior behavior or worse long-run equilibrium states. Though the definition is applied loosely in this research, both models show signs of the firefighting trap, described initially in Section 2.2.1. In the strategic model, the reflex of the government to increase suppression expenditures following a bad fire season begins a self-reinforcing feedback loop where preventative fuel removal is diminished and fuel is allowed to accumulate. Fuel also accumulates due to shorter fire durations caused by more suppression, though the effect of this relationship in the model is less significant than the impairment of the prevention budget because fuel accumulation also indirectly leads to longer fire durations through the negative effect of higher fireline intensities on firefighting combat efficiency. Nonetheless, more fuel in the system leads to more intense fires, more burned area, and thus further expenditures on suppression. In absence of an external intervention (which the current model structure disallows), the self-regulating behavior of the system continues to allocate resources to suppression in order to deal with the short-term problem of last year’s fire damages. While the occasional mild weather year may reduce the suppression budget temporarily, the large stock of fuel in the system ensures that the suppression budget more or less remains at the maximum in the long-run given large initial allocations to suppression.

In the operational model, the pressure to extinguish fires in the desired time horizon produces a balancing effect on the number of fires in the system *if* the ignition rate, and subsequent ignition spikes, are mild. The firefighters spend less time at each fire, but long enough to ensure that the fire is sufficiently suppressed. Under more extreme ignition rates, the added pressure to extinguish fires results in less time spent at each fire, which increases the probability of insufficient mop-up and therefore the rekindle rate. These rekindles represent rework that enters the stock of fires being fought as if they were brand new ignitions. The result is that the system gets trapped in a perpetual state of managing rekindled fires, increasing the long-run equilibrium number of fires in the system. While the number of fires in the system eventually must return to zero (as fuel is exhausted or torrential rains come, for example), the increase due to the rework process is indicative of the intervention system collapse that has occurred in the northern regions of Portugal during severe fire seasons.

Preventing or mitigating the firefighting trap is achieved through different means in each of the two models. In the strategic model, if the initial allocation of resources to prevention is high enough, then the excess fire damages that occur due to the trap can be curtailed since fuel levels remain more stable. Recall, however, that some amount of suppression is necessary to manage fires, both in the model and in reality (see Figure 36). Thus, if the initial allocation to prevention resources is too high, and by relation resources to suppression too low, then the increase in average fire durations leads to more burned area over time. In the operational model if the target fire duration is increased, then the severe pulses of sudden fire activity that cause the trap under shorter durations can ultimately be fully managed.

While the “solutions” to the firefighting trap in each model are straightforward and highly simplified, they represent important real-world tradeoffs for policymakers and fire managers. The strategic model does not attempt to reproduce in a statistically valid way the history of fire activity in Portugal, yet it is nonetheless a retrospective look at the tradeoffs between fire suppression and preventative fuel removal (or fuel management). 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 (refer back to the "Shifting the Burden" archetype in Figure 9) was to increase fire suppression capability in order to limit the damage of forest fires. Such a policy is attractive in the short-term; the public lauds decision makers for swiftly addressing the forest fire problem, and as fire durations decrease across the country the public is potentially even more appeased.

Strict adherence to fire suppression is unfortunately not sustainable in the long-run, as the combination of fuel accumulation and severe weather can overwhelm the suppression capacity of Portugal, as was the case in 2003 and 2005 (Figure 1). The strategic model reproduces these effects through the absolute changes in the total stock of forest fuel. However, fuel management is not concerned exclusively with fuel removal; the construction of fuel breaks and mosaics across the landscape are fuel management techniques that make suppression easier and more effective. In either case, fuel management investments are fundamental solutions focused on the underlying causes of forest fires in Portugal, but their lack of immediate short-term benefit make them less attractive to both the public and policymakers with finite terms of governance. However, their long-term benefit, particularly under increasing climate uncertainty, may ultimately override the short-term gain in suppression-driven policy (as was shown in Figure 35).

Important tradeoffs also exist in the operational management of forest fires during the summer season. There is an expectation, among government authorities and the public, that fires will not be allowed to burn for long periods of time near people and property. As a result, managers of fire crews attempt to deploy their resources such that the time spent at each fire is minimized (i.e. the fix in the "Fixes that Fail" archetype of Figure 10). Helicopters and aircraft with large payloads of water or fire retardant appear to be effective tools for extinguishing fires, and, perhaps more importantly to fire managers, they are encouraged by government authorities and lauded by the public. Such tactics may be sufficient under certain circumstances, but in extreme cases may lead to an abundance of rekindled fires.

Groundwork with tools is more time-consuming and laborious, and it does not have the same reassuring effect on the public, but the thoroughness of the practice reduces the incidence of rekindled fires. But spending more time at each fire, while it may decrease the probability of rekindle, means that other fires on the landscape are allowed to burn for longer. This is why in Figure 44 the peak number of fires in the system under the longer target is larger than the one under the shorter target. However, the longer target allows the system to escape the trap of perpetual rework, while the shorter target does not. Thus, there are tradeoffs between the two targets that influence the firefighters (they may need to work longer and harder), and also the public (fires may burn longer near their property).

These political tradeoffs must be addressed in decision making, but the reality is that longer targets decrease the probability of suppression system collapse. While the operational model is parameterized with constant time targets, it is clear that the time spent at each fire will be variable. And, under unique circumstances of very severe fire activity, it may simply be impossible to spend the necessary amount of time at each fire. Nonetheless, the longer target (which is really a surrogate for more comprehensive mop-up following initial attack) *can* mitigate the incidence of rekindles.

The models in this research have shown that additional fuel management and longer suppression time targets can curtail, or prevent, fire damages that manifest due to relevant socio-physical dynamics. While both policies may make logical sense, in the scope of the models and in reality, decision makers may be loath to implement them. As was discussed, the government and the public tend to favor large suppression capacities and advanced firefighting capability. Psychologically, fuel management and hand tools don’t instill the same feelings of security and safety despite being proven preventative mechanisms. Moreover, managers and decision makers rarely receive credit for fixing problems that never occur (Repenning & Sterman, 2002). One could argue that they simply *can’t* receive credit given that we can never attribute, with absolute certainty, the prevention of the problem to their actions.

The tradeoff between symptomatic and fundamental solutions in forest fire management highlights the role that technology plays in policymaking. In this day and age, a (highly) technological solution is often perceived as a good or just solution. Technology also provides a decision making crutch for policymakers, certainly in forest fire management but in most fields one could argue. Decision support systems are desirable technologies in forest agencies because the advanced computing puts all of the decisions behind a black box. The practical value of such technologies should be underscored, but overreliance makes decision makers less perceptive of underlying, systemic problems that may *not* be completely solvable by technology, or worse may be caused (indirectly) or exacerbated by the technology. Section 1.2 framed this thesis as a technology and policy problem complicated in different ways by socio-physical dynamics. After developing insights from the results, the significant role that technology plays in forest fire management should be clear. In both strategic and operational contexts, public and institutional pressure drives deployment of technological solutions, e.g. investments in new helicopters following a bad fire season or reliance on airborne water drops to suppress fires. This obsession with technology must be addressed not only by decision makers, but also in the media and public circles, if “low-tech” solutions that actually mitigate the underlying causes of fire, e.g. fuel management and hand tools, are to ever have a hope of being implemented.

The following section discusses the most important limitations of the System Dynamics models developed in this research.

5.2 Limitations of the Models

The models developed in this work teach important lessons about the side effects or unintended consequences of seemingly rational policies. The general causality governing each model makes logical sense in the scope of relevant literature and the testimonies of Portuguese fire experts during semi-structured interviewing. But, as was mentioned in Section 3.1, System Dynamics models are not useful for providing statistically valid estimates; rarely are they more than 40% accurate (Chahal & Eldabi, 2008). The strategic and operational models are, at best, demonstrations of the consequences of certain actions that arise due to self-regulating feedbacks in the systems. While the figures from Chapter 4 have absolute numerical axes, the numbers should not be taken at face value. Despite some parameterization with secondary data, the structure of both models is built around high-level interactions between social and physical variables, some of which have never before been measured (e.g. pressure). Thus, it is not the actual numbers that are significant when interpreting the results, but the trends, or dynamics, of important metrics (e.g. burned area, fires being fought) over time.

It is important to realize that the shape of the model trends are most sensitive to the table functions in the models linking variables for which a physical equation or significant statistical relationship does not exist. In the strategic model, these functions are the effect of fire intensity on combat efficiency (Figure 14), the effect of pressure to control fires on suppression expenditures (Figure 16), and the effect of the size of the prevention budget on fuel removal time delay (Figure 17). In the operational model the functions are the effect of the pressure on firefighters on the amount of time spent per fire (Figure 23) and the effect of time per fire on the probability of bad mop-up (Figure 24). In all of these functions the sign of the relationship (i.e. positive or negative) is logical, but the exact shape (i.e. range, domain, curvature) of the function is either based on anecdotal evidence from experts or informed guesses. Thus, an important question is how different function shapes affect the results.

5.2.1 Sensitivity Analysis of Table Functions

It should be evident that an infinite number of sensitivity tests could be conducted for *each* table function, let alone the five listed above. Moreover, the software used to develop the models does not appear to have in-house sensitivity analysis capability for table functions. Therefore, this section evaluates the impact of two simple shape changes, one that produces a stronger effect on the dependent variable and the other a weaker effect, on the table functions from each model (the table function for the effect of prevention budget on fuel removal time delay is not evaluated due to difficulty in sensitivity testing). Sensitivity is evaluated in terms of the effect on total burned area in the strategic model (discussed first) and fires being fought in the operational model. Each change is evaluated in isolation (i.e. all other parameters held constant) and all of the other simulation initial conditions are maintained (e.g. in the strategic model there is still an exogenous ramp increase to fuel growth starting at year 50).

Figure 45 shows the sensitivity of total burned area to changes in the shape of the table function relating relative fire intensity to combat efficiency. The effect of changes on focused prevention policy was negligible (excluded from the graph), but the effect on fire exclusion policy was large. A stronger (steeper slope) relationship between fire intensity and combat efficiency results in a faster acceleration of burned area, which makes sense given that combat efficiency affects the ability of crews to reduce fire duration.

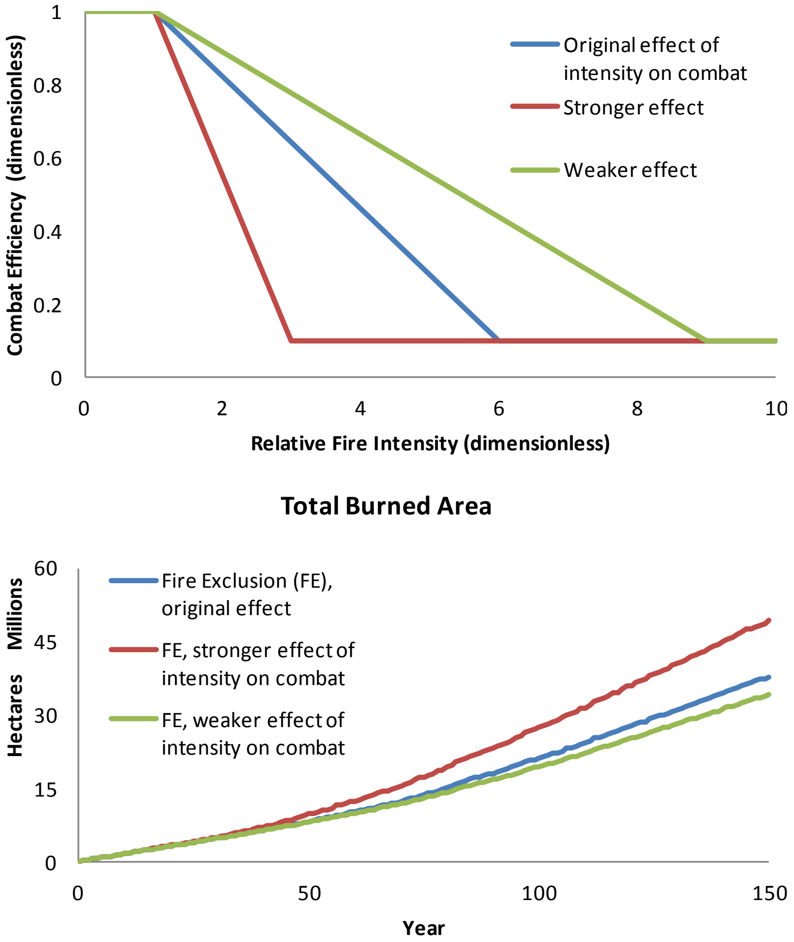


Figure 45. Sensitivity of total burned area to effect of fire intensity on combat efficiency (strategic model, fire exclusion policy).

Figure 46 shows the sensitivity of total burned area to changes in the shape of the table function relating the pressure to control fires to suppression expenditures. A much more pronounced step function leads to more burned area in the long-run under fire exclusion policy. Interestingly, this stronger effect leads to less burned area under focused prevention policy (excluded from graph). The reason is that more suppression forces result in shorter fire durations, and thus less burned area, but enough prevention resources are still available to keep fuel loads relatively stable. This suggests that the highly reflexive government response to bad fire years with more suppression expenditures may be acceptable provided enough of the budget is still set aside to fuel management efforts (and that these efforts are actually carried out, a subtle but very important point).

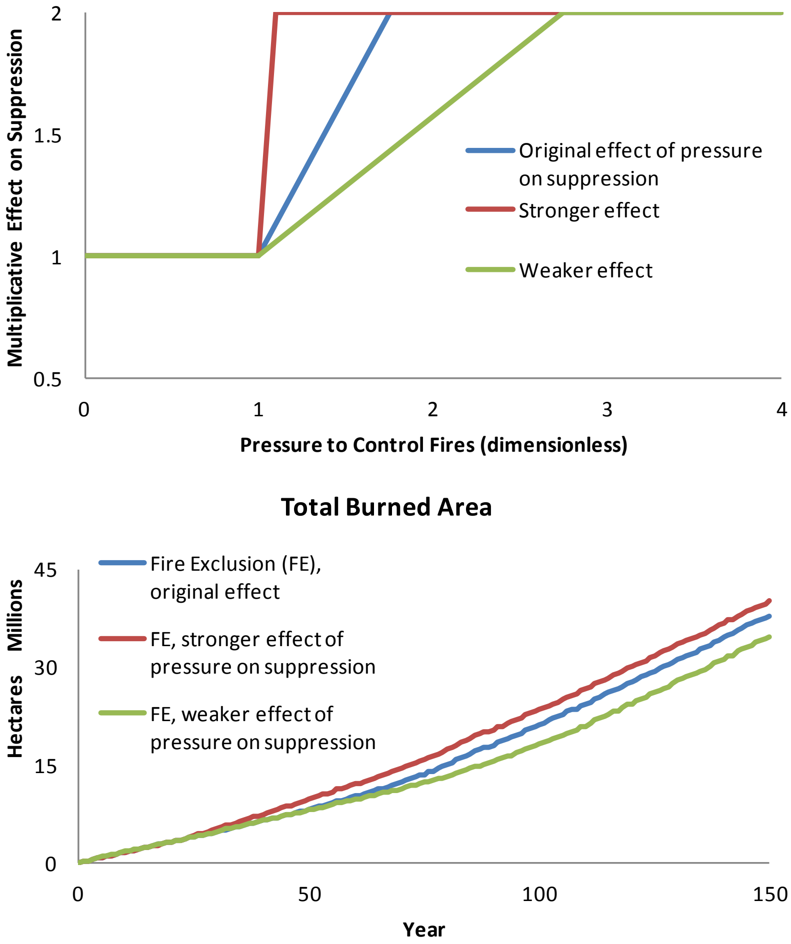


Figure 46. Sensitivity of total burned area to effect of pressure on suppression expenditures (strategic model, fire exclusion policy).

Figure 47 shows the sensitivity of fires being fought (in the operational model) to changes in the shape of the table function relating the pressure on firefighters to time per fire. In this case, a stronger effect between the two variables can be the difference between system collapse and system recovery under a 10-day 90% pulse to the ignition rate. Assuming a stronger effect, the number of fires in the system reaches a new, higher equilibrium level (similar to the

100% pulse in Figure 43) while a weaker effect shows faster system recovery to the starting level of fires in the system.

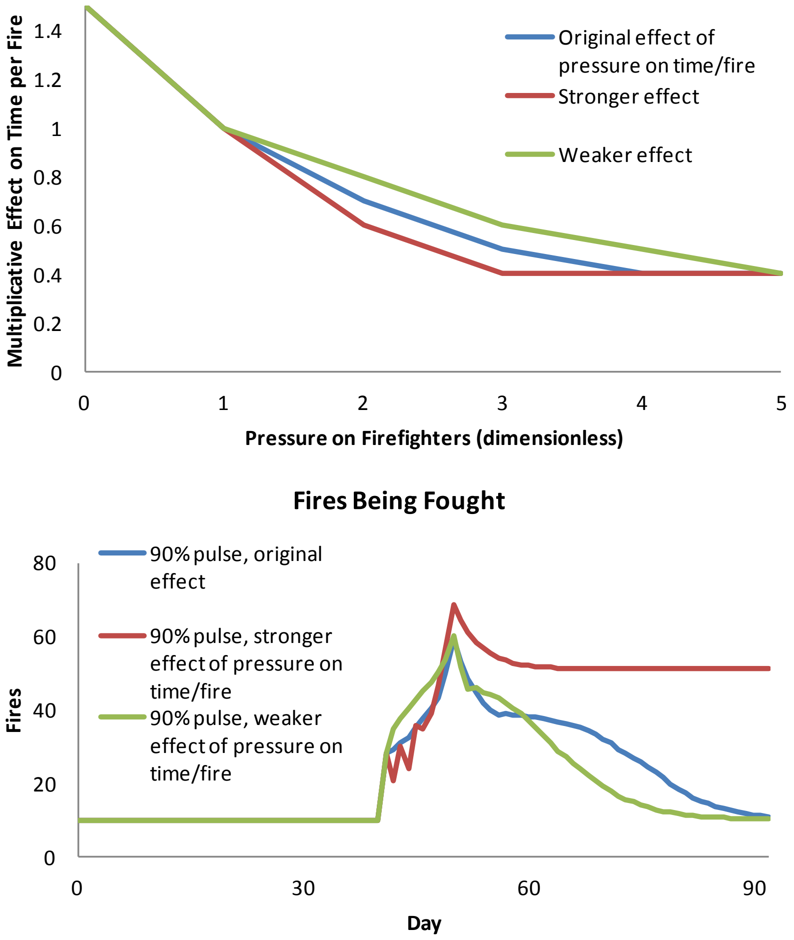


Figure 47. Sensitivity of fires being fought to effect of pressure on time per fire (operational model, 10-day 90% pulse).

Figure 48 shows the sensitivity of fires being fought to changes in the shape of the table function relating time per fire to the probability of bad mop up. Again, the shape of this table function can be the difference between system collapse and system recovery under a 10-day 90% pulse to the ignition rate. However, comprehending the shape of this function is more important than the previous one because the probability of bad mop up is what ultimately determines the amount of rework (rekindles) in the system. In other words, even if firefighters are spending 15 minutes on average at each fire (a time target that seems recklessly low), the extent to which this effects fire suppression performance depends on how these man-hour allocations affect the likelihood of rekindle. Maybe 15 minutes per fire only leads to a 5% chance of rekindle on average. While this may be unlikely, particularly in Portugal, better understanding these relationships is important for evaluating different policies on firefighting operations.

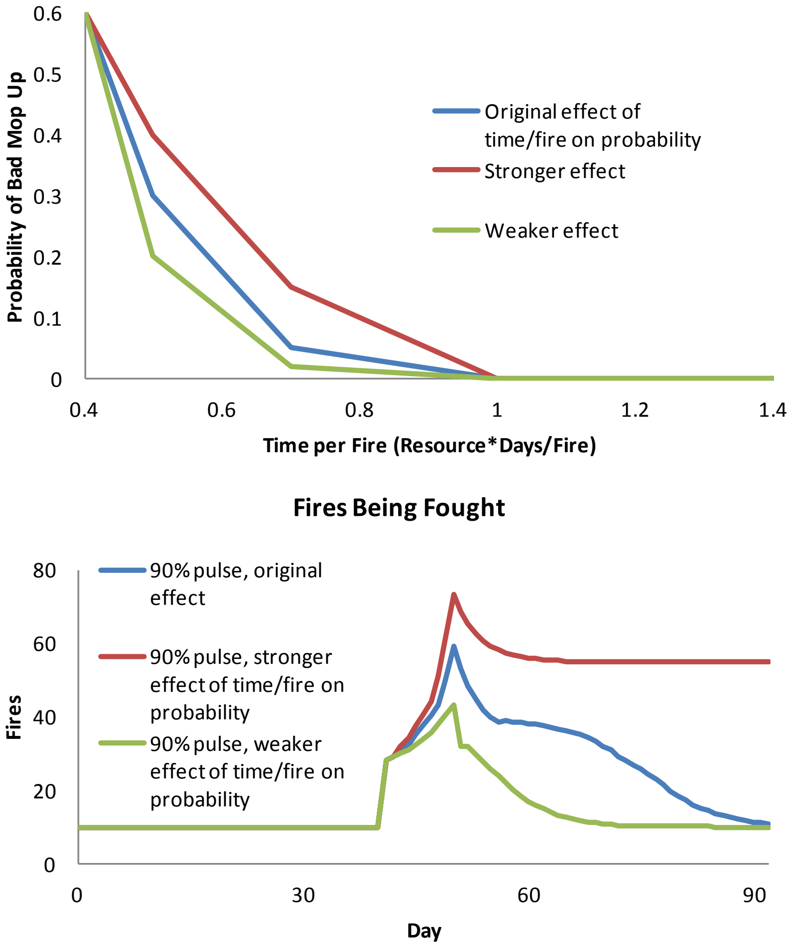


Figure 48. Sensitivity of fires being fought to effect of time per fire on probability of bad mop up (operational model, 10-day 90% pulse)

This section showed how sensitive the model results are to changes in the table functions. While sensitivity analysis is important, what this section really indicates is that more data needs to be collected in order to relate these variables in a more statistically rigorous way. Developing experiments or ethnographic studies, for example, to measure the impact of firefighting pressure on time spent per fire could be a research thesis by itself, but in order to guide organizational decision making such work is necessary. The shape of most of the table functions is therefore a limitation of this research. However, given that the direction of the relationship is correct, insights obtained from the dynamics are still significant and useful. The following section discusses another limitation of this research, and most studies that utilize System Dynamics.

5.2.2 Determinism is not Reality

While System Dynamics is useful for gaining holistic 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 in Portugal, are subject to great uncertainties. A lot of this uncertainty stems from the fact that humans are constantly interacting with the systems in an attempt to change their state. As a result, a deterministic simulation model of a system, based on timeless relationships between social and physical/technical factors, can never be a true representation of the system over time.

This limitation is particularly evident in the strategic model. 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 amount of resources dedicated to prevention. The only way prevention resources change is based on how suppression resources change following a given fire year. Thus, following a bad fire year, the system will always invest heavily in suppression for the current year, whereas investing heavily in fuel management is also a perfectly legitimate (and some might judge better) budget decision. To suggest that the 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. This point, while it highlights the limitations of deterministic models, also makes a subtle case for how they can be useful.

The strategic and operational models produce dynamics based on highly simplified interconnections between social and physical variables, many of which have been aggregated into abstract concepts (e.g. pressure to control fires). Such model structures, and the corresponding results, serve two important functions. One, the visual depiction of the causal linkages between variables, though deterministic, is easy for non-technical people to follow. Relevant stakeholders and decision makers can therefore examine the structure and provide critique on how to improve the model. For this reason System Dynamics models, when developed with the participation of stakeholders, have been coined *learning laboratories*.

The second important function has to do with interpreting the results. Due to simplifying assumptions and sparse datasets, let alone determinism, System Dynamics modelers do not put faith in their predictions of future system states. However, the simulations do provide rough prospective analyses of what can occur over time if the system is allowed to evolve under the causal logic posited in the structure. While the strategic model developed in this research does not allow the user to make exogenous investments in preventative fuel removal during the simulation, the user can nonetheless witness the potential impact of negative feedbacks in the system. The user may look at the model results at year 100 and say, this is when fuel treatments should have been conducted. Engaging decision makers, particularly stakeholders with competing objectives or beliefs, with the model structure/logic and outputs in this way is useful for starting a discussion about the systemic impacts of decision making in forest fire management. People begin to realize that their decisions, and the outcomes of their decisions, do not manifest only within their organization or institution; they can affect other parts of the forest fire management system, sometimes in very non-obvious ways.

In spite of the results from this research and their implications, the following chapter discusses additional issues and obstacles surrounding policy implementation in Portugal in order to make recommendations.

Chapter 6. Toward Policy Implementation

Regardless of how elegant or innovative a model is, or how compelling its results are, using it to develop actionable and effective policy in many ways is the largest undertaking. Suppose, for example, that after reviewing the results of the operational model, fire managers in Portugal are sufficiently convinced of the merits of longer suppression time targets as a means of reducing rekindles. Convincing people who live on the wildland urban interface (WUI) of these merits, however, is another challenge entirely, since they would prefer to have fires near their homes extinguished as quickly as possible.

Indeed, there is a vast array of different challenges to policy implementation. Many are bureaucratic in nature; one of the shortcomings of democracy and checks and balances is the sluggishness with which new policies (or laws) are passed. Yet other challenges arise from the number of stakeholders invested in a major problem. A large number of stakeholders compounds the bureaucracy problem, lengthening the time it takes to agree on policy changes. Kenneth Arrow's Impossibility Theorem (1963) underscores this dilemma, proving that no voting system can turn individual preferences into a community-wide decision without violating a specific set of necessary criteria. In other words, there does not exist a policy that can please everyone using voting. Nonetheless, implementing policy within large fire management institutions and government authorities ultimately requires the consent of the people.

Figure 49 displays a simplified picture of the policymaking process by identifying the major steps during policy analysis, formulation, and implementation. This chapter uses this figure as a guide for making policy recommendations. To a large extent, Chapter 1 covered problem definition, though this chapter will identify further issues and conditions that complicate the policymaking process. The bulk of this research used analytic methods, namely System

Dynamics, to identify, at least at a systemic level, alternatives for improving policy. This chapter evaluates the feasibility of those alternatives through discussion of the relevant stakeholders and their corresponding functions, and the impediments to implementation that stem from competing stakeholder objectives and additional social and physical factors unique to Portugal. Finally, this information is synthesized into general recommendations, as well as specific next steps in both the strategic and operational domains (Appendix D: Case Study Research Plan and Appendix E: Rekindle Mitigation Project, respectively). Much of this chapter is informed by semi-structured interviews with Portuguese fire experts from academia, industry, and government.

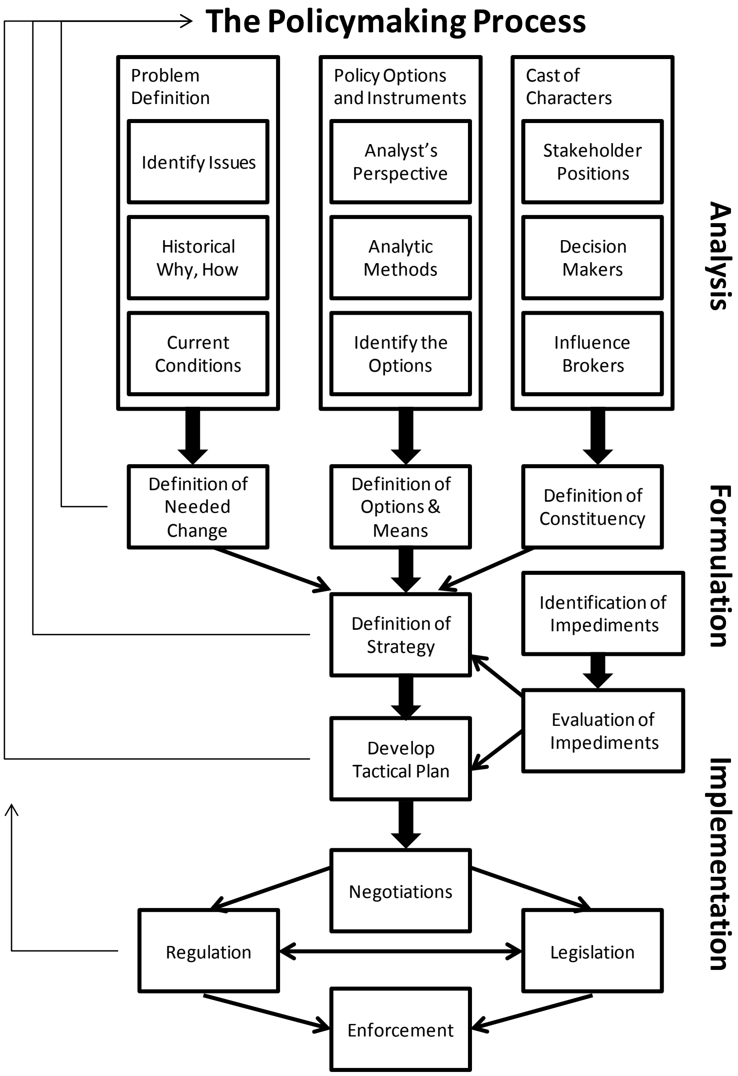


Figure 49. Outline of the policymaking process, particularly useful in complex, interconnected systems, adapted from the MIT Technology and Policy Program.

6.1 Relevant Stakeholders

Since forest fires are a national problem in Portugal, numerous public and private stakeholders suffer consequences when they are poorly managed. Figure 50 maps the major stakeholder groups and their interactions. The Ministry of Agriculture (Ministério Agricultura Desenvolvimento Rural e Pescas) and the Ministry of Interior (Ministério Administração Interna) in the federal government together guide the nation's forest fire management plans. The Forest

Authority (AFN, Autoridade Floresta Nacional) is responsible for "structural" prevention, which largely includes preventative efforts made during the fire offseason. The agency pays salaries to forest technicians in every municipality, as well as to *sapadores florestais*, a type of technician adept at prescribed burning and mop-up activities. These technicians report to the federal government during the peak fire season (Charlie Phase: July 1st to September 30th), but otherwise may report to non-industrial private landowners or forest owners' associations during the rest of the year.

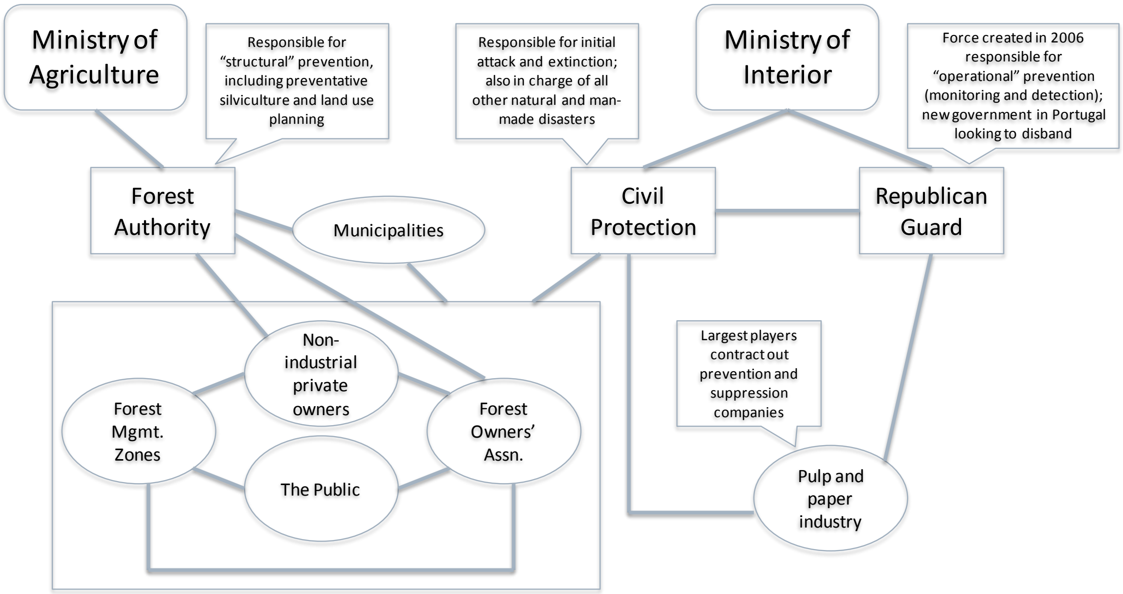


Figure 50. Map of stakeholders and interactions within the national forest fire management system.

Forest owners' associations are essentially groups of non-industrial private landowners who collectively manage their lands in order to profit from timber sales and/or protect against fire. Leaders of these associations must work with regional government, the pulp and paper industry, and conservation agencies when they want to engage in any fuel management effort, such as prescribed burning. Yet another collective management body exists, called forest intervention zones (ZIFs, Zonas de Intervenção Florestais). ZIFs are part of a 2005 government initiative to better manage forest properties under risk of fire. These zones may comprise multiple non-industrial private land owners and forest owners' associations, though unlike the associations, the leadership of these zones can receive funding from the federal government for planning and formation, as well as for doing fuel management work (though the ZIFs are not reimbursed until after completing the work).

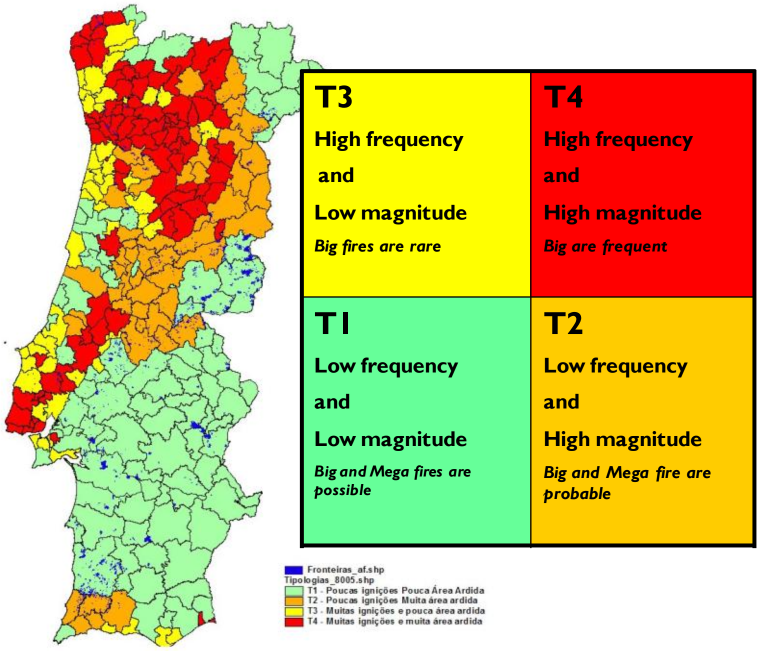
The Republican National Guard (GNR, Guarda Nacional Republicana) is responsible for "operational" prevention, which includes surveillance and monitoring of the landscape in order to detect fires early. While GNR can provide some initial attack against newly ignited fires, their primary role is to report fires to the Civil Protection Authority (ANPC, Autoridade Nacional de Protecção Civil), which is in charge of suppressing and extinguishing the fires. Unfortunately, there are far too many ignitions each year for ANPC to handle, so each municipality also maintains varying capacities of volunteer firefighters. These volunteers are employed throughout the fire season, but are typically not well-trained since firefighting is not their main profession. The pulp and paper industry, given that the forests are their most valuable asset, contract out to fire suppression companies, such as Afocelca, during the peak season. They also employ forest technicians of their own to conduct preventative treatments throughout the rest of the year.

The major takeaway from Figure 50 is that forest fire management in Portugal is decentralized, overlapping, and sufficiently complex due to the multitude of stakeholders (several additional stakeholder groups were omitted for clarity in the map). The following section highlights additional barriers, in addition to the complex stakeholder network, that impede implementation of the results derived from this research.

6.2 Impediments to Implementation

Consider the policy implications of the strategic model (Section 5.1), namely that more preventative fuel removal, as opposed to suppression capacity expansion, could mitigate frequency and severity of fires in Portugal. Experts in the fire community agree that fuel accumulation can lead to future, more severe fire seasons. Most, but not all, agree that too much fire suppression can cause dangerous fuel accumulation. The strategic SD model was built around these two claims, and thus the results are consistent with the hypothesized outcomes. It is possible that translating expert, and largely academic, opinion into a simple and transparent simulation model could increase, or at least facilitate understanding of these concepts among policymakers and the public. An equally likely outcome is that despite understanding and agreeing with the model insights, policymakers may never use them to make policy changes.

What are some potential reasons for this outcome? For one, the fire risk across municipalities in Portugal (*concelhos*) is widely variable (Figure 51). Due to the relatively low risk of fire in Southern Portugal, regional decision makers are not likely to deem fuel treatments cost-effective, nor is it likely that the negative feedbacks of the strategic model are as pronounced in the south. On the contrary, Northern Portugal is subject to much more intense fire activity. Population density on the WUI (i.e. more potential ignition sources) and the flammable oils of the eucalyptus are major contributors to the elevated fire risk. The diversity of fire risk across the country makes national policy on fuel management, or fire management in general, difficult to justify since “one-size-fits-all” policies will likely be ineffective and expensive. However, despite the elevated fire risk in Northern Portugal, regional governments continue to invest heavily in more suppression resources. While fuel removal from eucalyptus stands may not be cost-effective due to the tree’s large yield, the potential firefighting benefits of a fuel break network have yet to be realized.



T3 **High frequency** **and** **Low magnitude** ***Big fires are rare***	**T4** **High frequency** **and** **High magnitude** ***Big are frequent***
T1 **Low frequency** **and** **Low magnitude** ***Big and Mega fires are possible***	**T2** **Low frequency** **and** **High magnitude** ***Big and Mega fire are probable***

Figure 51. Fire risk typified across municipalities in Portugal (Oliveira, 2011a).

A further hindrance is the highly fragmented, private land ownership structure of Central and Northern Portugal. Figure 52 shows the distribution of rural property sizes across municipalities in Portugal and the absolute number of properties in five major regions. Comparing Figure 51 and Figure 52 shows that fire risk is correlated with fragmented land ownership. Regional authorities may be becoming increasingly aware of the benefits of fuel management, but under such a complicated land ownership structure, the coordination across landowners of an agreed upon treatment may just be too time-consuming and costly. Furthermore, companies from the pulp and paper industry, such as gPS, assert that the return on investment in fuel management is often too low.

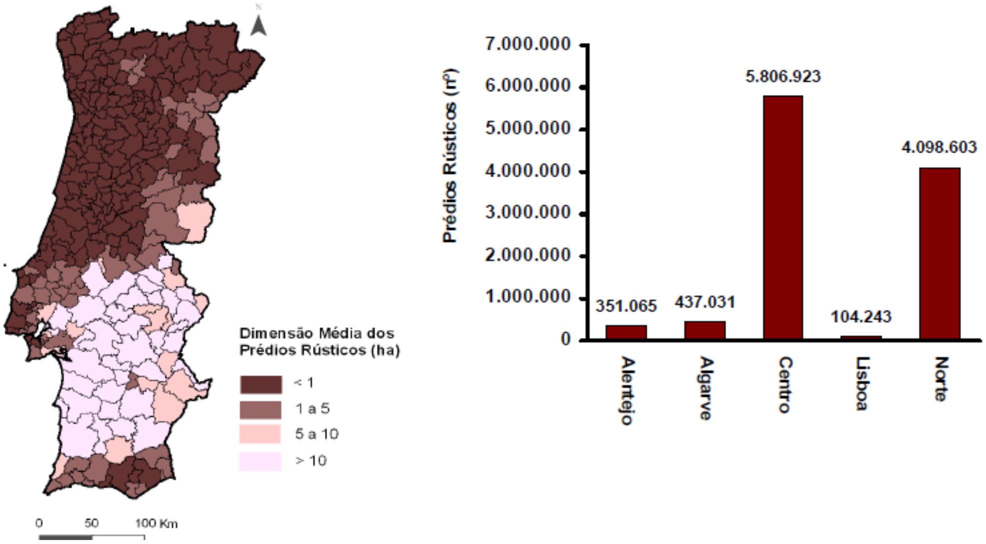


Figure 52. Distribution of average rural property size (ha) across Portugal (left) and number of properties in each major region (right) (Oliveira, 2011a).

On the operational end it is possible that managers of national and regional fire suppression forces are aware of the rekindle problem, particularly in the north. But, there are obstacles for actually putting the knowledge into practice. As mentioned above, many of the firefighters in Portugal who respond to forest fires are volunteers, paid at meager hourly rates. What incentive does a volunteer fire crew have to do more time-consuming and laborious groundwork if their wage does not reflect the additional work? What disincentive does a volunteer fire crew have to prematurely abandon a fire that appears to be extinguished if there is no monetary penalty for doing so? The answers to these questions demonstrate the challenge of instituting longer suppression time targets and more comprehensive mop-up activities. Effectively coordinating the operations of regionally dispersed volunteer firefighters, in addition to the overlapping, in terms of both time and space, jurisdiction of different organizations, is a serious challenge. Some argue that Portugal actually possesses an adequate suppression capacity for responding to the large number of fires during the summer but lacks an effective central command system for managing all of the crews and resources (Beighley & Hyde, 2009; Gomes, 2006). During periods of high fire activity, lack of coordinated command can amplify the rekindle problem as too many crews are dispatched to the same site or not enough to another, while important, time-sensitive information is not shared across organizations.

The overlapping jurisdiction problem manifests at the regional level when decision makers seek to carry out beneficial fuel treatments. The agencies and organizations with overlapping jurisdiction often have competing objectives. For instance, conducting a prescribed burn in Valongo, a municipality of Porto district on the WUI, requires authorization from the interior and environmental departments of Valongo, gPS, one or more forest owners' associations, and the Institute for Nature Conservation and Biodiversity (ICNB, Instituto da Conservação da Natureza e da Biodiversidade), a national agency responsible for protected areas in Portugal. If the prescribed burn will span properties of multiple owners, a likely scenario in the highly fragmented north of Portugal, affected companies, forest owners' associations, and nonindustrial private owners will need to coordinate and implement the burn. Furthermore, while the burn may alleviate future fire risk to the region, the local environmental department and/or the ICNB may oppose the burn due to the potential environmental impact on sensitive or protected areas. What results is a bureaucratic process for prescribing fuel treatments to the region, leading to politicized debate and value judgments that ultimately stall important management actions. As is the case with most democratic nations, the public often weighs in on such issues as well.

In the U.S., public acceptance of fuel management (which again includes chemical treatment and mechanical thinning in addition to prescribed burning) has been explored via numerous social science methods (Brunson & Shindler, 2004; Shindler & Toman, 2003; Toman et al., 2011; Winter et al., 2002). All of these studies generally argue against "one-size-fits-all" policies, but indicate that public support for fuel management is generally high. In addition, the correlation between agency trust and public acceptance of fuel management has been measured using surveys (Absher & Vaske, 2011) and in tandem with focus group interviews (Winter et al., 2004). However, all of the above studies were conducted in the U.S. No such study was found in the literature where the sample consisted of Portuguese people. Given that the culture or ethos of a community can vary significantly across regions, results from other studies regarding public support for fuel management should be applied warily to the Portuguese situation. Nonetheless, it is evident the public support impacts the success of such programs, making data collection of such perceptions in Portugal a vital research effort (see Appendix D: Case Study Research Plan).

On an individual level, the decision to support fuel management programs or to conduct a (legal) prescribed burn on one's property ultimately boils down to economics. The aftermath of rural abandon in Portugal has left many forest properties in the rural inlands unattended and unmaintained by their owners, many of whom inherited the land but have since migrated to the coastal cities. While some use these properties as vacation getaways during the summer, many are unlikely to spend money better managing their lands if they receive little or only distant direct financial benefit from doing so. The market for lumber in other parts of the world allows nonindustrial private landowners to sell their wood for profit, but this structure is lacking in Portugal. Similarly, fuel management programs, whether at the national or regional scale, are unlikely to be supported if landowners believe the cost to outweigh the financial benefit of being marginally more protected from fire. Again, the fragmented land ownership in Portugal complicates these decisions, mostly in the form of free-riding. Fuel management by one landowner will decrease fire risk to neighboring landowners, so while the benefit is distributed only the first landowner bears the cost. As a result, owners have less incentive to act unilaterally.

Another potentially insidious obstacle to policy implementation arises when stakeholders or the public simply do not believe in the merits of the policy. How can a forest owners' association in Northern Portugal hope to carry out what they believe to be a critical prescribed burn across a high fuel load landscape if the mayors of the affected towns believe prescribed burning to be a useless and dangerous practice? While the bulk of fire science is grounded in known facts supported by physics, including the fact that rate of fire spread increases with fuel load, managing forest fires in Portugal is a highly contextual affair that varies based on region across social and physical dimensions. Because forest fire management is a complex socio-technical system (what was referred to in Section 3.1 as a CLIOS) and plagued by multiple uncertainties, establishment of universal fact or decision rules for managing fires is difficult, if not impossible. Furthermore, even in the presence of widely agreed upon facts, policy development can be slowed by non-believers. As Stone (1997) pointed out, facts are relative. Aside from a few universal facts, most are contested, where subjective value judgments and rhetoric are used to construe the meaning of what most might call objective truths. The democratic decision making process facilitates these subjective debates about facts, making widely supported policy all the more difficult to craft. A good analog is global climate change.

6.3 Recommendations and Next Steps

In light of these impediments, what are the appropriate measures to take for improving forest fire policy in Portugal? Research from this work indicates that public pressure to control fires forces the government to invest in more suppression technology even though this decision may result in more burned area in the long run. Unfortunately, it is unlikely that this cause-and-effect mechanism will subside in the future. After all, is it not the purpose of the government to respond to public pressures, even if these pressures lead to shortsighted decision making? The political incentive to ignore public pressure, assuming the policymakers want to be reelected, just is not there.

What then can policymakers do, in addition to investing in suppression technology, to mitigate the consequences of forest fires? Regardless of approach, three things must be done: (1) assemble a sufficient coalition of stakeholders, (2) pass the policy, law, or regulation, and (3) maintain coalition to facilitate implementation. These three steps essentially distill Figure 49 into the major requirements of the policymaking process.

Model results indicate that preventative fuel removal is a useful strategy for mitigating fire severity, but its effectiveness may only be realizable at large scale. To facilitate landscape-scale fuel management programs, policymakers will need to generate a sufficient coalition of dedicated constituents, which means better aligning the incentives of effected stakeholders. Further developing the country-wide ZIF network represents a promising government initiative for coordinating the efforts of multiple land owners and forest owners' associations across the diverse regions of Portugal.

ZIFs are practical because instead of being centrally managed by the federal government in Lisbon, the authority to carry out fuel management programs is placed in the hands of an elected leadership that has contextual knowledge of the particular region where the ZIF resides. ZIFs also seek to set up an infrastructure for harvesting and selling wood within the zone such that profits can be reinvested in the region to further protect from fire and bolster the harvesting infrastructure. Furthermore, the law enabling the creation of ZIFs was already passed, in 2005. Unfortunately, maintaining a coalition of supporters for ZIFs has proven to be a challenge.

Currently, there seems to be a divide between ZIF leadership and the federal government over how much and to what end government funds should be allocated. This divide, in part, stems from the newness of the initiative, specifically the lack of standard operating procedures for fund allocation and monitoring of ZIF activity. While 150 ZIFs are in the planning and formulation process, only three have been approved by AFN and little actual fuel management has been conducted to date (Beighley & Hyde, 2009). In order for the money allocated to ZIFs to be used toward its desired end, a standard set of protocols needs to be established and enforced by the government. ZIFs are a legal mechanism for collectively managing the forests; as such, the financial obligation from the government and the fuel management obligation from the ZIF need to be unambiguous and enforced in a consistent and reliable manner. This way, fund availability is dependable and wasteful or ineffective fuel management programs are minimized.

ZIF management is still complicated by the land ownership structure in certain parts of Portugal (Figure 53). As a result, the aforementioned problems of free-riding and economic disincentives still apply. Financial incentives, such as tax rebates for doing prescribed burns on one's land, are a potential mechanism for getting private landowners to take action for public benefit. Under savvy and cohesive leadership, ZIFs may also be capable of using moral suasion to provoke landowner action, similarly to how labor unions function. Navigating this collective action problem to defend against forest fires will be difficult in Portugal, but ZIFs, if financed and managed effectively, nonetheless represent a promising legal mechanism for overcoming this policy impediment.

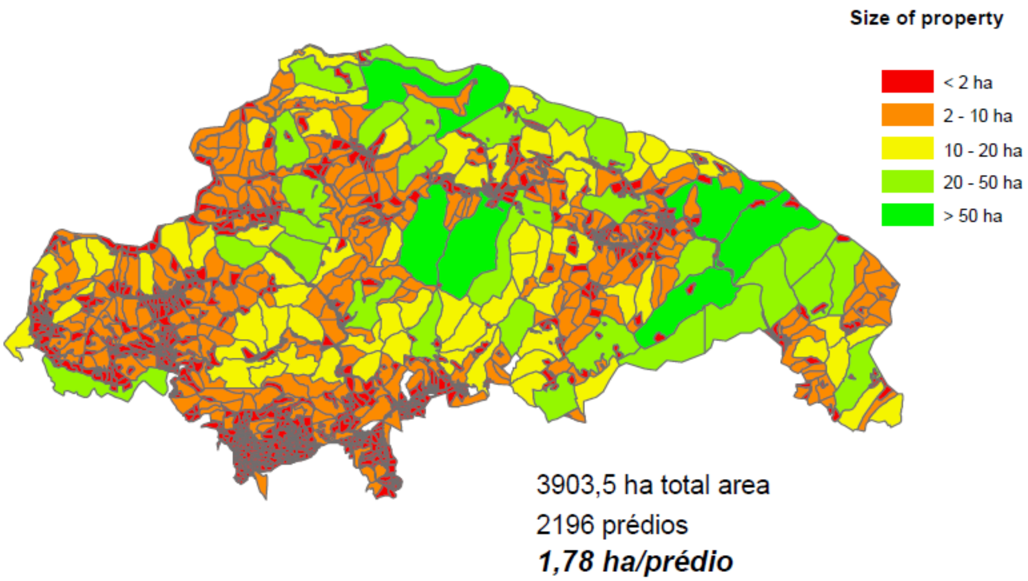


Figure 53. ZIF in Cansino (Monchique), Portugal. Average size of member property is 1.78 hectares (~4.4 acres).

When considering the complex stakeholder network, various policy barriers, as well as the numerous social (e.g. demographics, population density, law enforcement, regional government, influence of private owners) and physical (e.g. land cover, vegetation types, forest yields for private owners, terrain, weather, climate) factors that distinguish regions in Portugal, it is clear that a decentralized approach to policy development is warranted. As a result of the regional diversity, perceptions about the relative merits of suppression versus fuel management will vary, as will the year-to-year investments in the two activities by the regional governments. The strategic SD model is general, thus many of the relationships between variables, particularly the nonlinear table functions, could be very different across regions. There may also be additional factors and causal links not modeled currently that are essential to understanding the regional context of forest fire management.

Case study research on different regions is useful for ascertaining the effect of the aforementioned differences on regional forest fire policy. Furthermore, insights from this higher resolution research will likely lead to more specific recommendations concerning ZIF management in or around the case study sites. A research plan for this undertaking is provided in Appendix D: Case Study Research Plan.

Unlike strategic forest fire management decisions, whose outcomes manifest over long time scales, testing the impact of policy changes on the incidence of rekindles is easier to carry out. Appendix E: Rekindle Mitigation Project outlines a plan for a demonstration project of the benefit of longer suppression time targets on rekindle incidence. The demonstration project is implementable by any fire suppression organization, but is targeted at Afocelca, the fire suppression company that gPS contracts with in the summertime to protect their forest properties. The project can be carried out over the course of the fire season (several months), making it easier to glean the benefit (or potential cost) of policy change. Furthermore, gPS has the authority to act unilaterally in making such a change since doing so only directly affects their property. As a private company, the only people they have to convince are the shareholders. While this may be a challenge, the complications arising from unaligned stakeholder incentives discussed earlier largely do not apply. Nonetheless, important considerations and relevant obstacles to effectively carrying out the demonstration project, and subsequently interpreting outcomes to improve fire suppression policy within the organization, are discussed in Appendix E: Rekindle Mitigation Project.

Chapter 7. Conclusions and Future Research

This research used System Dynamics to evaluate the side effects and unintended consequences of strategic and operational decision making in forest fire management in Portugal. The work is intended to be a descriptive study of the major feedbacks that affect system performance in each context, though the implications were used to develop preliminary recommendations. The findings from the models convey the significant effect of social influence on system behavior, as well as the interconnectedness between human decision making and forest response (i.e. fuel accumulation, rekindling of fires). In both cases, the system can get trapped in worse long-run states due to the overwhelming effect of negative feedbacks, specifically:

- Excessive year-to-year investment in fire suppression may mitigate fire damages in the short-term, but in the long-term can undermine preventative efforts, which becomes increasingly problematic as fuel accumulates.
- Aggressive suppression targets may sufficiently extinguish fires under mild ignition rates, but during extreme fire activity (not uncommon in Northern Portugal) may lead to insufficient mop-up, which increases the incidence of rekindles and thus fires to suppress.

With the insights from this research, national and regional policymakers, as well as fire managers for suppression organizations in Portugal, should better appreciate the interconnected systems in which their authorities reside and the dynamics that may undermine seemingly rational policies.

7.1 Contributions

This research has both academic and applied contributions. In two different temporal contexts, it shows how technology, in this case fire suppression technology, cannot be the sole means for solving fire management problems given the underlying dynamics that undermine effectiveness over time. It therefore extends the study of technology and policy, and engineering systems broadly, by exploring how public and institutional pressures force what may be suboptimal technology-driven solutions. The work extends the field of forest fire management by developing a dynamic, systemic model where the majority of previous work, particularly in Portugal, has been static and more narrowly defined. Finally, this research extends the System Dynamics literature by exploring two separate manifestations of policy resistance and the firefighting trap in forest fire management that arise under different contextual, though similar systemic circumstances.

While the operational model is in many ways unique to the high number of human-caused ignitions in Portugal, the strategic model builds on an already longstanding debate between the relative merits of suppression versus prevention investments. Its insights are therefore applicable to other fire-prone countries, particularly those that have traditionally relied on policies of fire exclusion (e.g. Southern Europe and the U.S.).

7.2 Future Research

The SD models developed in this research have many possible extensions, as well as applications in future work. As it stands, the strategic model can evaluate different initial suppression and prevention allocations in terms of their effect on total burned area. Future work could apply costs to different suppression and prevention activities, so that the sum of managerial costs and fire damages is evaluated across alternative allocations. Furthermore, cost-constrained decision making could be made at later time periods in the model, instead of deciding on just one allocation in the beginning. Under these conditions the user can use past information on how the system behaved in order to update decision making and make exogenous interventions accordingly. Despite resembling the structure of a dynamic program, the primary purpose of such an extension would not be to develop an optimal solution, but to better facilitate user understanding of how decision making affects system dynamics and vice versa.

Another area of future work involves expanding the physical and political systems in the model. In the forest system an additional flow out of the fuel stock representing timber harvesting could be modeled under the basic rules that define harvest scheduling models. Increased burned area leads to land homogenization, which further facilitates increased burning due to lack of fuel breaks. This process could be modeled endogenously, though doing so may require that the model become spatially explicit (recall that it is currently aspatial). In the political system, there are many other factors besides burned area in the previous year that dictate spending decisions on suppression resources, such as government turnover and financial situation (particularly relevant in Portugal now). It is worth noting that expanding the model boundaries to include other endogenous processes needs to be traded off against increased model complexity and subsequent difficulty in interpreting results.

Finally, while many academics and practitioners agree that some amount of fuel management is beneficial to forest fire management, how best to execute the treatments is not well understood, particularly in Portugal. The difficulty in fuel management goes beyond just the alleged government reflex toward suppression; fuel management in Portugal is complicated by fragmented private land ownership. Future work should investigate the factors affecting fuel treatment decision making for individual landowners, forest owners’ associations, and private companies. Modeling these decisions across stakeholders will inform landscape-level fuel treatment beyond simply an increase to prevention resources.

The operational model was developed to demonstrate a very specific unintended consequence of fire suppression tactics in Portugal. However, the model can be extended by including a variety of other feedback loops that affect the incidence of rekindles. For example, fatigue or burnout is a major determinant of the quality of suppression work done at each fire. If fire crews are tired, they may be more likely to abandon mop-up so that they can go back to the base and rest. The model could also make the labor force, and therefore net resources, endogenous to the amount of fires being fought in the system. In other words, when ignitions spike in the summer, more crews and resources are acquired to respond to the fires. This happened during the severe conditions of the 2003 and 2005 fire seasons in Portugal, where additional fire crews, engines, and aircraft were leased from neighboring countries. By attaching unit costs to these resources, users could combine suppression time target policies with acquisition decisions in order to evaluate the tradeoffs between cost and susceptibility of the system to collapse. However, as was discussed with regard to the strategic model, the descriptive advantage of expanding the model boundary needs to be evaluated against the difficulty in interpreting results, such that meaningful policy prescriptions can actually be made.

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Appendix A: List of Meetings

Over the course of this research, I attended numerous meetings with national authorities, university experts, and other relevant stakeholders to the project. Table 2 lists individual trips and/or semi-structured interviews in which I partook, while Table 3 lists visits and meetings where attendees included myself and other FIRE-ENGINE team members. I'd like to acknowledge once again the patience and cooperation practiced by all stakeholders whom I've met with since beginning work on this project.

Table 2. Individual trips and semi-structured interviews.

Date	Region	Organization	Contact
06-27-2011	Lisbon	AFN	João Pinho
06-27-2011	Lisbon	ISA	José Miguel Pereira
07-08-2011	Valongo	gPS	Ricardo Mendes
07-08-2011	Valongo	Municipal Civil Protection	José António Gonçalves
07-12-2011	Vila Real	UTAD	Paulo Fernandes
07-13-2011	Lisbon	CAP	João Soveral
07-13-2011	Lisbon	ANPC	João Verde
07-28-2011	Porto	UCP	Américo Mendes
08-02-2011	Porto	FORESTIS	Rosário Alves
01-19-2012	Porto	AFN	Paulo Mateus

Table 3. FIRE-ENGINE meetings and visits.

Date	**Region**	**Organization**	**Purpose**
03-20-2011	Amarente	gPS	Visit to plantations
03-20-2011	Valongo	gPS	Visit to plantations
03-24-2011	Setúbal	ISA, UTAD, INESC, MIT	FIRE-ENGINE workshop
03-25-2011	Setúbal	ISA, UTAD, INESC, MIT	FIRE-ENGINE workshop
03-25-2011	Setúbal	gPS	Visit to paper plant
06-16-2011	Lisbon	CAP	Informal meeting
06-16-2011	Lisbon	GIPS	Informal meeting
07-25-2011	Figueira da Foz	Afocelca	Observe operations
07-27-2011	Vila Real	UTAD, GIF	Observe operations
07-27-2011	Valongo	gPS	Observe operations
11-28-2011	Porto	CAP, FORESTIS, gPS, AFN, INESC, MIT	Stakeholder meeting

Appendix B: Strategic Model Documentation

The following is a list of fully documented strategic model variables that is automatically generated by the System Dynamics software used in model development (Vensim). Justification for variable parameterization is included where possible.

(01) Average Area Burned per Fire=3.14159*(Radial Rate of Spread*Fire Duration)^2
Units: (Meters*Meters)/(Fire*Fire)
Assumes that every fire grows at a constant radial rate (no acceleration component) in the shape of a circle; at the end of the fire duration the fire is completely extinguished. Result derived to match data from (AFN, 2010).

(02) Budget Adjustment Time=3
Units: Years
The average time required to adjust the current budget to the new proposed budget following a bad fire year.

(03) Burned Area per Year=Fires per Year*Average Area Burned per Fire*Burned Area Units Conversion
Units: Hectares/Year
The number of hectares burned per year. In equilibrium, the yearly burned area should closely match the 10 year average from 2001-2010.

(04) Burned Area Units Conversion=0.0001
Units: (Hectares*Fire)/(Meters*Meters)
Necessary unit conversion from square meters to hectares.

(05) Change in Pink Noise = (White Noise - Pink Noise)/Noise Correlation Time
Units: 1/Year
Change in the pink noise value; Pink noise is a first order exponential smoothing delay of the white noise input.

(06) Combat Efficiency=Normal Combat Efficiency*Effect of Intensity on Combat
Units: Dimensionless
Determines how substantial the decrease to fire duration is based on additional suppression resources; value should be constrained between 0 and 1 for realism and tractability (lower values decrease fire duration slower).

(07) Effect of Fuel Availability on Rate of Spread=Table for Effect of Fuel Availability on Rate of Spread(Relative Fuel Availability)
Units: Dimensionless
Determines the effect of relative fuel availability on the rate of spread.

(08) Effect of Intensity on Combat=Table for Effect of Intensity on Combat(Relative Fire Intensity)
Units: Dimensionless
Determines the effect of relative fire intensity on the combat efficiency of firefighting resources.

(09) Effect of Pressure on Suppression=Table for Effect of Pressure on Suppression(Pressure to Control Fires)
Units: Dimensionless
Describes the effect of increasing pressure to control fires on increases in the suppression budget.

(10) Effect of Prevention on Fuel Removal=Table for Effect of Prevention on Fuel Removal(Relative Prevention Budget)
Units: Dimensionless
Determines the effect of prevention resources on fuel management effectiveness; more resources, not surprisingly, increases the effectiveness of fuel management.

(11) Exogenous Fuel Growth=Initial Fuel Growth*Input
Units: Tons/Year
The exogenous fuel growth rate can be configured to include a range of test inputs. It is set to the product of the initial fuel growth rate and the test input. The test input allows users to specify a range of input patterns, including a step, pulse, ramp, cycle, and pink noise, or combinations of these.

(12) FINAL TIME = 150
Units: Year
The final time for the simulation.

(13) Fire Duration=Maximum Fire Duration*EXP(-Combat Efficiency*(Suppression Budget/Total Fire Budget))
Units: Minutes/Fire
The average duration of fires; uses the basic fire economics model developed by (Sparhawk, 1925) and the principle of diminishing marginal returns from additional suppression resources by using an exponential decay function.

(14) Fireline Intensity=Radial Rate of Spread*Fuel Load*Fuel Heat of Combustion*Fireline Intensity Units Conversion
Units: KJ/(Seconds*Meters)
Also known as Byram's fireline intensity or frontal fire intensity, it is the rate of heat energy released per unit time per unit length of the fire front, regardless of the depth of the flame zone (Byram, 1959). Higher fireline intensities make

fire suppression more difficult, thus lengthening the duration of the fire.

(15) Fireline Intensity Units Conversion=1/600
Units: (Minutes*Hectares*Kg)/(Seconds*Meters*Meters*Tons)
Necessary unit conversion to calculate fireline intensity.

(16) Fires per Year=RANDOM NORMAL(FPY Min, FPY Max, Normal Fires per Year, FPY Standard Deviation, Noise Seed 0)
Units: Fires/Year
The number of fires that occur per year; randomized based on historical data.

(17) Forest Burning=Burned Area per Year*Fuel Load
Units: Tons/Year
Amount of fuel burned each year through accidental burning.

(18) Forest Fuel= INTEG (Fuel Growth-Forest Burning-Preventative Removal, Normal Fuel Load*Total Forested Area)
Units: Tons
The accumulation of forest fuel in the region, net of prescribed and accidental burning, measured in metric tons (1 metric ton = 1000 kg).

(19) FPY Max=36000
Units: Fires/Year
Maximum number of ignitions that can occur in a given year; informed by (AFN, 2010).

(20) FPY Min=18000
Units: Fires/Year
Minimum number of ignitions that can occur in a given year; theoretically zero but a nonzero minimum is established from the past 10 years of data in (AFN, 2010).

(21) FPY Standard Deviation=0
Units: Fires/Year
The standard deviation input into the normally distributed yearly ignitions random variable; a standard deviation of 4000 more or less covers the possible range of values based on historical data.

(22) Fraction of Budget to Prevention=1/3
Units: Dimensionless
The fraction of the budget allocated to prevention activities. The Fire Exclusion Policy mix has 40% prevention, 60% suppression. The Focused Prevention Policy mix has 75%

prevention, 25% suppression.

(23) Fraction of Budget to Suppression=1-Fraction of Budget to Prevention
Units: Dimensionless
The fraction of the budget allocated to suppression activities.

(24) Fuel Growth=Exogenous Fuel Growth
Units: Tons/Year
Forest fuel growth per year; assumed to be exogenous (for now).

(25) Fuel Heat of Combustion=18620
Units: KJ/Kg
The fuel's heat or energy content, assumed constant across all fuels; this is a reasonable assumption given that the heat of combustion does not vary much across fuel types. Number informed from <http://www.forestencyclopedia.net/p/p531>.

(26) Fuel Load=Forest Fuel/Total Forested Area
Units: Tons/Hectare
Fuel load is defined as the number of metric tons of forest fuel per hectare; main descriptor of fuels because it determines fire intensity and the difficulty of fire suppression.

(27) Fuel Removal Time Delay=Normal Fuel Removal Time Delay*Effect of Prevention on Fuel Removal
Units: Years
This amount of time governs the capability of forest managers to remove fire prone fuels from the landscape. With more resources to prevention activities, the timeliness with which the fuels can be removed increases, thus draining the stock faster.

(28) Hot Weather Multiplier=RANDOM NORMAL(0, 2, 1, Weather Standard Deviation, Noise Seed 0)
Units: Dimensionless
Normally distributed random variable between 0 and 2 used to simulate fluctuations in yearly weather (i.e. temperature, dryness, relative humidity, etc.). Informed by (Li et al., 1997).

(29) Initial Fuel Growth= INITIAL(Normal Yearly Forest Burning + Normal Yearly Preventative Removal)
Units: Tons/Year
Initial fuel growth is set equal to the sum of normal yearly burned fuel and normal yearly managed fuel such that the system begins in equilibrium.

(30) Initial Suppression Budget=Total Fire Budget*Fraction of Budget to Suppression

Units: Euros/Year
The initial budget for suppression activities.

(31) INITIAL TIME = 0
Units: Year
The initial time for the simulation.

(32) Input=1+STEP(Step Height, Step Time)+(Pulse Quantity/Pulse Duration)*PULSE(Pulse Time, Pulse Duration)+RAMP(Ramp Slope, Ramp Start Time, Ramp End Time)+Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+STEP(1,Noise Start Time)*Pink Noise
Units: Dimensionless
Input is a dimensionless variable which provides a variety of test input patterns, including a step, pulse, sine wave, and random noise.

(33) Maximum Fire Duration=136
Units: Minutes/Fire
The maximum duration of burning for an average fire.

(34) Net Change in Budget=(Suppression Expenditures-Suppression Budget)/Budget Adjustment Time
Units: Euros/Year/Year
First order information delay that seeks to adjust the suppression budget to what was proposed in the previous year.

(35) Noise Correlation Time=5
Units: Year
The correlation time constant for Pink Noise.

(36) Noise Seed=0
Units: Dimensionless
Random number generator seed. Vary to generate a different sequence of random numbers.

(37) Noise Seed 0= 0
Units: Dimensionless
Random number generator seed. Vary to generate a different sequence of random numbers.

(38) Noise Standard Deviation=0
Units: Dimensionless
The standard deviation of the pink noise process.

(39) Noise Start Time=0
Units: Year
Start time for the random input.

(40) Normal Combat Efficiency=1
Units: Dimensionless
The baseline efficiency with which firefighting forces can decrease the duration of fires through additional suppression resources.

(41) Normal Fire Duration=Maximum Fire Duration*EXP(-Normal Combat Efficiency*(Normal Suppression Budget/Total Fire Budget))
Units: Minutes/Fire
The "normal" duration of burning for a given fire. Number derived to match data of average area burned per fire from (AFN, 2010).

(42) Normal Fireline Intensity=Normal Radial Rate of Spread*Normal Fuel Load*Fuel Heat of Combustion*Fireline Intensity Units Conversion
Units: KJ/(Meters*Seconds)
Represents the "normal" fireline intensity under "normal" burning conditions.

(43) Normal Fires per Year=24528
Units: Fires/Year
The "normal" (or average) number of forest fires occurring each year. Number informed by (AFN, 2010); it is the average of the past 10 years (2001-2010).

(44) Normal Fuel Load=10
Units: Tons/Hectare
The "normal" (or average) amount of fuel per hectare of forested area; represents "normal" burning conditions. Number is informed from (Fernandes, 2001).

(45) Normal Fuel Removal Time Delay=10
Units: Years
The "normal" fuel management time delay under "normal" budgetary policy. The delay is measured in units of time. Thus, one can think of very effective fuel management as taking a smaller amount of time to implement and execute.

(46) Normal Suppression Budget=1e+008
Units: Euros/Year
The suppression budget under normal conditions, which in this case we assume to be the heavy suppression scenario since it most closely describes current conditions in Portugal.

(47) Normal Prevention Budget=5e+007
Units: Euros/Year
The prevention budget under normal conditions, which in this

case we assume to be the heavy suppression scenario since it most closely describes current conditions in Portugal.

(48) Normal Radial Rate of Spread=2
Units: Meters/Minute
Represents the "normal" (or average) radial rate of fire spread under "normal" fuel load conditions. Number is informed by (Fernandes, 2001; Fernandes et al., 2009).

(49) Normal Yearly Burned Area=Normal Fires per Year*3.14159*(Normal Radial Rate of Spread*Normal Fire Duration)^2*Burned Area Units Conversion
Units: Hectares/Year
Represents the "normal" amount of burned area each year; calculated based on "normal" input parameters.

(50) Normal Yearly Forest Burning=Normal Yearly Burned Area*Normal Fuel Load
Units: Tons/Year
Represents the "normal" amount of burned fuel each year; calculated based on "normal" input parameters.

(51) Normal Yearly Preventative Removal=(Normal Fuel Load*Total Forested Area)/Normal Fuel Removal Time Delay
Units: Tons/Year
Represents the "normal" amount of fuel removed each year through fuel management techniques.

(52) Pink Noise = INTEG(Change in Pink Noise,0)
Units: Dimensionless
Pink Noise is first-order autocorrelated noise. Pink noise provides a realistic noise input to models in which the next random shock depends in part on the previous shocks. The user can specify the correlation time. The mean is 0 and the standard deviation is specified by the user.

(53) Pressure to Control Fires=Burned Area per Year/Normal Yearly Burned Area
Units: Dimensionless
Dimensionless measure of political pressure that dictates further expenditures on suppression budget. Bad fire years (large area burned) will increase this political pressure.

(54) Preventative Removal=Forest Fuel/Fuel Removal Time Delay
Units: Tons/Year
Amount of fuel removed each year through prescribed burning and other fuel management activities.

(55) Prevention Budget=Total Fire Budget-Suppression Budget

Units: Euros/Year
The amount of funds available for prevention activities;
increases in the suppression budget drains funds from the
prevention budget.

(56) Pulse Duration=1
Units: Year
Duration of pulse input. Set to Time Step for an impulse.

(57) Pulse Quantity=0
Units: Dimensionless*Year
The quantity to be injected to customer orders, as a fraction of
the base value of Input. For example, to pulse in a quantity
equal to 50% of the current value of input, set to 0.5.

(58) Pulse Time=10
Units: Year
Time at which the pulse in Input occurs.

(59) Radial Rate of Spread=Normal Radial Rate of Spread*Effect of Fuel Availability on Rate of Spread
*Hot Weather Multiplier
Units: Meters/Minute
The radial rate of spread of fires is the product of normal
spread, the effect from fuel availability and weather.

(60) Ramp End Time=100
Units: Year
End time for the ramp input.

(61) Ramp Slope=0
Units: 1/Year
Slope of the ramp input, as a fraction of the base value (per
year); slope of 0.01 into fuel growth is used to simulate afforestaiton and rural abandon in Portugal (from year 50 to 100).

(62) Ramp Start Time=50
Units: Year
Start time for the ramp input.

(63) Relative Fire Intensity=Fireline Intensity/Normal Fireline Intensity
Units: Dimensionless
The relative intensity of the fireline, over or under what is
considered normal under normal burning conditions.

(64) Relative Fuel Availability=Fuel Load/Normal Fuel Load

Units: Dimensionless
The relative accumulation of fuel over what is considered normal for normal burning conditions.

(65) Relative Prevention Budget=Prevention Budget/Normal Prevention Budget
Units: Dimensionless
The relative amount of resources available to prevention activities.

(66) SAVEPER = TIME STEP
Units: Year [0,?]
The frequency with which output is stored.

(67) Sine Amplitude=0
Units: Dimensionless
Amplitude of sine wave into the input (fraction of mean).

(68) Sine Period=4
Units: Year
Period of sine wave in customer demand. Set initially to 4 years to simulate the business cycle.

(69) Step Height=0
Units: Dimensionless
Height of step input, as fraction of initial value.

(70) Step Time=5
Units: Year
Time for the step input.

(71) Suppression Budget= INTEG (Net Change in Budget, Initial Suppression Budget)
Units: Euros/Year
The amount of funds available for suppression resources. This budget is used to decrease the average duration of fires in an effort to decrease burned area and damages.

(72) Suppression Expenditures=MIN(Initial Suppression Budget*Effect of Pressure on Suppression, Total Fire Budget)
Units: Euros/Year
Yearly expenditures on suppression activities is the product of the normal budget and the multiplicative increase due to political pressure.

(73) Table for Effect of Fuel Availability on Rate of Spread([(0,0)-(9,3)],(0,0),(0.5,0.71),(1,1),(2,1.41),(3,1.73),(4,2),(6,2.45),(8.99,3),(9,3))
Units: Dimensionless
The lookup function used to determine the effect of relative

fuel availability on rate of spread. Concave function
(approximately the square root function) informed by the
experimental work of Paulo Fernandes.

(74) Table for Effect of Intensity on Combat([(0,0)-(10,1)],(0,1),(1,1),(6,0.1),(10,0.1))
Units: Dimensionless
Lookup function used to determine effect of fire intensity on
fire combat ability; general idea behind the shape of the
function is informed by the last paragraph of
<http://www.forestencyclopedia.net/p/p487>.

(75) Table for Effect of Pressure on Suppression([(0,0.8)-(4,2)],(0,1),(1,1),(1.75,2),(4,2))
Units: Dimensionless
The lookup function used to determine the effect of political
pressure on additional suppression expenditures. The general
shape of the function is informed by discussions with José
Miguel, João Soveral, and Paulo Fernandes, who all speak to the
"reflex" of government to spend a lot of money on new
suppression equipment and vehicles following a bad fire year
(basically a step function).

(76) Table for Effect of Prevention on Fuel Removal([(0,0)-(3,3)],(0,3),(0.2,3),(1,1),(2.95,0.35),(3,0.35))
Units: Dimensionless
The lookup function used to determine the effect of the relative
amount of prevention resources on fuel management effectiveness.

(77) TIME STEP = 1
Units: Year [0,?]
The time step for the simulation.

(78) Total Burned Area= INTEG (Burned Area per Year, 0)
Units: Hectares
The accumulation of burned area over the lifetime of the simulation.

(79) Total Fire Budget=1.5e+008
Units: Euros/Year
The total amount of money allocated to fire management activities.

(80) Total Forested Area=6.14e+006
Units: Hectares
Total forested area of the region; assumed to be exogenous over
the lifetime of the simulation.

(81) Weather Standard Deviation=0
Units: Dimensionless

The standard deviation input into the normally distributed
weather random variable. Standard deviation of 0.5 covers a
range of weather multipliers from 0.1 to 1.9, standard deviation
of 0.28 covers a range from 0.7 to 1.3.

(82) White Noise=Noise Standard Deviation*((24*Noise Correlation Time/TIME STEP)^0.5*(RANDOM UNIFORM
(0,1, Noise Seed) - 0.5))
Units: Dimensionless
White noise input to the pink noise process.

Appendix C: Operational Model Documentation

The following is a list of fully documented operational model variables. As before, justification for variable parameterization is included where possible.

(01) Bad Mop Up Rate=Potential Suppression Rate*Probability of Bad Mop Up
Units: Fires/Day
The rate at which fires are insufficiently mopped up due to fire suppression time targets, pressure from other larger fires, and fatigue, among other factors (only the time target is modeled explicitly, but others could be included if deemed useful).

(02) Change in Pink Noise = (White Noise - Pink Noise)/Noise Correlation Time
Units: 1/Day
Change in the pink noise value; Pink noise is a first order exponential smoothing delay of the white noise input.

(03) Desired Suppression Rate=Fires Being Fought/Target Fire Duration
Units: Fires/Day
The rate at which fires should be suppressed given the target fire duration.

(04) Effect of Pressure on Time per Fire=Table for Effect of Pressure on Time per Fire(Pressure on Firefighters)
Units: Dimensionless
A multiplier effect due to increased pressure on time per task.

(05) Effect of Time per Fire on Probability=Table for Effect of Time per Fire on Probability(Time per Fire)
Units: Dimensionless
Self-explanatory.

(06) Exogenous Fire Ignition Rate=Initial Fire Ignition Rate*Input
Units: Fires/Day
This is the exogenous fire ignition rate, which uses the input ariable to add pulses, steps, ramps, and sine waves to the fire ignition rate.

(07) FINAL TIME = 92
Units: Day
The final time for the simulation.

(08) Fire Ignition Rate=Exogenous Fire Ignition Rate
Units: Fires/Day
This is the number of fires entering the system each day.

(09) Fire Suppression Rate=Potential Suppression Rate*(1-Probability of Bad Mop Up)
Units: Fires/Day

The rate at which fires are suppressed; uses min function to
bound suppression rate.

(10) Fires Being Fought= INTEG (Fire Ignition Rate + Rekindle Surface Rate-Bad Mop Up Rate-Fire Suppression Rate, Initial Fire Ignition Rate*Target Fire Duration)
Units: Fires
The stock of fires currently being fought.

(11) Fires Suppressed= INTEG (Fire Suppression Rate, 0)
Units: Fires
The number of fires suppressed at any given time.

(12) Initial Fire Ignition Rate= INITIAL(20)
Units: Fires/Day
This is the initial fire ignition rate, assumed to be the rate in equilibrium.

(13) INITIAL TIME = 0
Units: Day
The initial time for the simulation.

(14) Input=
1+STEP(Step Height,Step Time)+
(Pulse Quantity/Pulse Duration)*PULSE(Pulse Time,Pulse Duration)+
RAMP(Ramp Slope,Ramp Start Time,Ramp End Time)+
Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+
STEP(1,Noise Start Time)*Pink Noise
Units: Dimensionless
Input is a dimensionless variable which provides a variety of
test input patterns, including a step, pulse, sine wave, and
random noise.

(15) Net Resources=20
Units: Resources
The (arbitrary) number of resources, i.e. trucks, engines
available for fire suppression.

(16) Noise Correlation Time=7
Units: Day
The correlation time constant for Pink Noise.

(17) Noise Seed= 2
Units: Dimensionless
Random number generator seed. Vary to generate a different
sequence of random numbers.

(18) Noise Standard Deviation=0

Units: Dimensionless
The standard deviation of the pink noise process.

(19) Noise Start Time=0
Units: Day
Start time for the random input.

(20) Pink Noise = INTEG(Change in Pink Noise,0)
Units: Dimensionless
Pink Noise is first-order autocorrelated noise. Pink noise provides a realistic noise input to models in which the next random shock depends in part on the previous shocks. The user can specify the correlation time. The mean is 0 and the standard deviation is specified by the user.

(21) Potential Suppression Rate=Net Resources/Time per Fire
Units: Fires/Day
Potential suppression rate given current resources and the average time spent per fire.

(22) Pressure on Firefighters=Desired Suppression Rate/Standard Suppression Rate
Units: Dimensionless
A dimensionless measure of pressure that accumulates as the stock of fires being fought grows.

(23) Probability of Bad Mop Up=Effect of Time per Fire on Probability
Units: Dimensionless
Represents the fraction of fires that go into the stock of rekindles; the remainder are suppressed.

(24) Pulse Duration=10
Units: Day
Duration of pulse input. Set to Time Step for an impulse.

(25) Pulse Quantity=0
Units: Dimensionless*Day
The quantity to be injected to customer orders, as a fraction of the base value of Input. For example, to pulse in a quantity equal to 50% of the current value of input, set to .50.

(26) Pulse Time=40
Units: Day
Time at which the pulse in Input occurs.

(27) Ramp End Time=1e+009
Units: Day

End time for the ramp input.

(28) Ramp Slope=0
Units: 1/Day
Slope of the ramp input, as a fraction of the base value (per year).

(29) Ramp Start Time=0
Units: Day
Start time for the ramp input.

(30) Rekindle Surface Rate=Rekindles Waiting to Burn/Surfacing Delay
Units: Fires/Day

(31) Rekindles Waiting to Burn= INTEG (Bad Mop Up Rate-Rekindle Surface Rate,0)
Units: Fires
This is the stock of fires that have yet to burn via rekindling;
they represent the stock of rework waiting to be finished.

(32) Resource Productivity=Fire Suppression Rate/Net Resources
Units: Fires/Resource/Day

(33) SAVEPER = TIME STEP
Units: Day [0,?]
The frequency with which output is stored.

(34) Sine Amplitude=0
Units: Dimensionless
Amplitude of sine wave in customer orders (fraction of mean).

(35) Sine Period=184
Units: Day
Period of sine wave in customer demand. Set initially to 4 years
to simulate the business cycle

(36) Standard Suppression Rate=Net Resources/Standard Time per Fire
Units: Fires/Day
The suppression rate under standard circumstances, i.e. when
there is an equilibrium number of fires in the system.

(37) Standard Time per Fire=1
Units: Resource*Day/Fire
Arbitrary measure of the man-hours required per fire.

(38) Step Height=0
Units: Dimensionless
Height of step input to customer orders, as fraction of initial value.

(39) Step Time=0
Units: Day
Time for the step input.

(40) Surfacing Delay=4
Units: Day
This is the average time it takes for a fire that was insufficiently mopped up to become an active fire via a rekindling.

(41) Table for Effect of Pressure on Time per Fire([(0,0)-(5,1.5)],(0,1.5),(1,1),(2,0.7),(3,0.5),(4,0.4),(5,0.4))
Units: Dimensionless
Table function showing that as pressure increases, time per fire decreases; this function quantifies how the low fire duration target manifests in less time spent per fire on average.

(42) Table for Effect of Time per Fire on Probability([(0.4,0)-(1.5,1)],(0.4,0.6),(0.5,0.2),(0.7,0.02),(1,0),(1.5,0))
Units: Dimensionless
Table function quantifying how too little time per task leads to an increase in probability of poor mop up.

(43) Target Fire Duration=0.5
Units: Day
The target fire duration puts pressure on firefighters to extinguish fires in a short time horizon; it is the indirect cause of poor mop up as firefighters are constantly pressured to move onto the next fire.

(44) Time per Fire=Standard Time per Fire*Effect of Pressure on Time per Fire
Units: Day*Resource/Fire
The average time (really man-hours) spent per fire, which decreases as pressure builds.

(45) TIME STEP = 1
Units: Day [0,?]
The time step for the simulation.

(46) White Noise=Noise Standard Deviation*((24*Noise Correlation Time/TIME STEP)^0.5*(RANDOM 0 1() - 0.5))
Units: Dimensionless
White noise input to the pink noise process.

Appendix D: Case Study Research Plan

This appendix presents a research plan to investigate regional forest fire management practice and beliefs in Portugal. As was mentioned in Section 6.3, the high-level dynamics generated by the strategic model paint a simple, generalized picture of national decision making in strategic forest fire management. The vastly different social and physical characteristics of regions in Portugal mean that their policies, as well as the general structure and actual mathematical relationships linking variables in the model, may diverge considerably from what was presented in this research. The following research plan seeks to explore and describe these divergences through a mixed-method, multiple case study design.

The proposed research attempts to answer the following two research questions using social science methods:

1. How do relevant decision making bodies in Portugal respond to bad fire years in terms of expenditures to suppression versus fuel management?
2. Do these decision making bodies believe that fuel management could be used to reduce the severity of large, intense fires in Portugal?

Answering Question 1 will reveal whether or not regional (and national) decision making authorities do in fact revert to suppression-based spending in light of public pressures and the worsening fire problem. With regard to Question 2, fuel management has been proven effective at reducing ignition probability and extent of fire spread, but not at large scale. Answering this question will reveal whether fuel management is perceived as a worthwhile landscape-scale fire management practice among various regional actors.

Research Design

Preliminary semi-structured interviewing and the quantitative SD modeling carried out in this thesis suggest that excessive suppression may self-reinforce further suppression, which undermines fuel management efforts and leads to larger burned areas over time (i.e. the aforementioned firefighting trap of short-term corrective action). While this hypothesis is unsubstantiated, answers to the two above research questions will (1) indicate whether regional decision making bodies revert to suppression spending following bad fire years, and (2) whether fuel management is perceived to be an effective practice for mitigating the damage of large fires. These answers, which will likely vary across regions in Portugal, will provide important behavioral evidence for further evaluating this hypothesis.

To develop answers to the research questions, a mixed methods research design will be carried out; a schematic of this design is shown in Figure 54. The design uses multiple case studies and employs qualitative and quantitative research methods to both explore and describe forest fire management practice and beliefs vis-à-vis the two research questions. Each case is a unit of analysis, where each case represents the collective decision making body of a region (i.e. case study site). Ultimately a small group of people, or perhaps one agency, makes decisions about where resources are allocated to manage forest fires in a region, but the collective input and opinions of regional stakeholders (refer to Figure 50) will undoubtedly influence decision making (hence the term "collective decision making body"). In reference to an earlier example, a large expenditure to a new fuel management practice is unlikely to be realized unless regional forest owners, environmentalists, and other people affected agree that it will be useful. Thus, many different kinds of people affect decision making; this research proposes to engage as many relevant stakeholders as possible in order to provide answers to the two research questions. In a multiple case study design, the cases are selected according to replication logic, not sampling logic (Yin, 2009). In other words, cases are selected based on known similarities and differences in specific contexts, which include both physical and social factors.

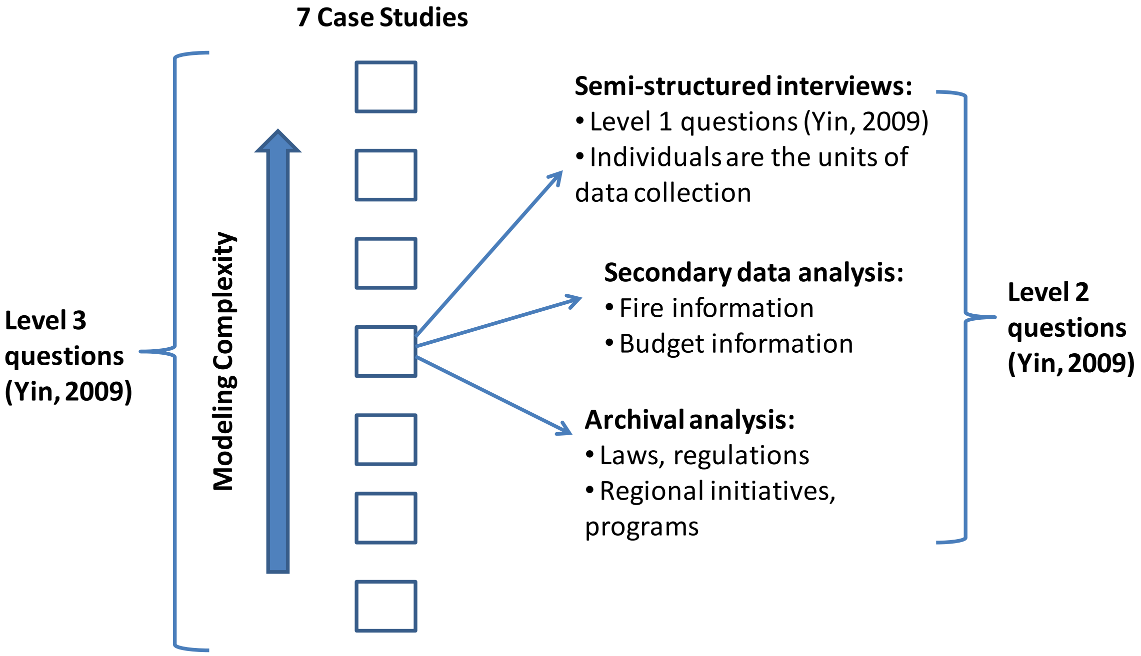

Figure 54. Schematic of multiple case study design employing mixed methods.

A case study design was chosen because emphasis on context and detail is important in forest fire management in Portugal since regions vary extensively across multiple dimensions. Yearly ignitions (Figure 55) and burned area (Figure 56) for example vary dramatically in the 18 districts of Portugal. In particular, note the districts of Porto and Guarda. In general, Porto experiences a high number of yearly ignitions, yet the effect of these ignitions on burned area is small (i.e. each ignited fire must be very small on average). On the contrary, in Guarda there aren't many yearly ignitions yet burned area is higher on average than in many of the other districts. In addition, there are other physical (e.g. land cover, vegetation types, forest yields for private owners, terrain, weather, climate) and social (e.g. demographics, population density, law enforcement, regional government, influence of private owners) variables that differentiate regions. Case study selection should try and capture the spectrum of these variables.

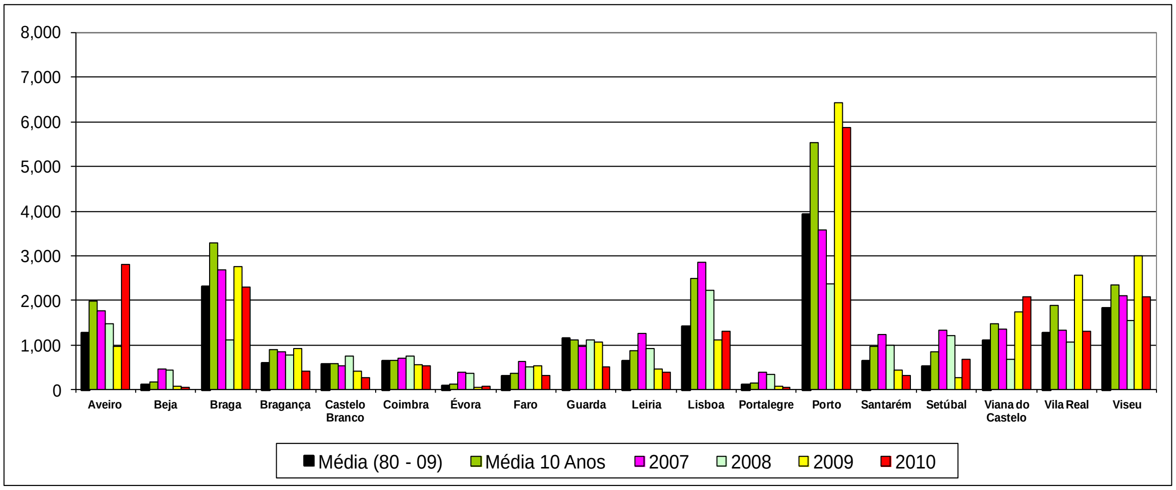

Figure 55. Number of ignitions across the 18 districts of Portugal (AFN, 2010).

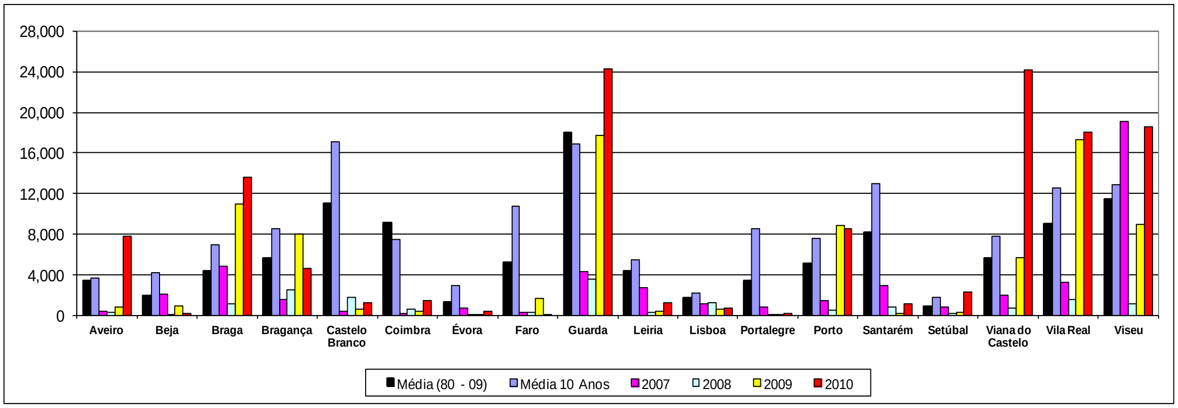

Figure 56. Burned area across the 18 districts of Portugal (AFN, 2010).

Seven cases were selected (shown in Figure 57) based on extended discussion with the head of forest protection for the Portuguese paper and pulp company grupo Portucel Soporcel (gPS), Tiago Oliveira, as well as other FIRE-ENGINE team members. Each case consists of two or more adjacent concelhos (municipalities) and can be thought of as the aforementioned collective decision making body with regard to forest fire management and policy. Each unit (case) has different physical attributes and consists of different public and private actors impacting decision making. Tiago and his colleagues at gPS have multiple contacts, professional experience, and specific knowledge in each of these seven cases, making in-depth observation and analysis of each one easier to facilitate. The complexity of the cases across some important physical and social dimensions is organized from high to low in Table 4. While there are only seven cases in the proposed research, they encapsulate a wide spectrum of forest fire management implications. This “representativeness” should quell most threats to external validity since the differences are indicative of the entire forest fire management problem in Portugal. However, generalizability of results from Portugal should be applied warily to other countries, where other factors defining regions may not be captured in the seven Portuguese cases.

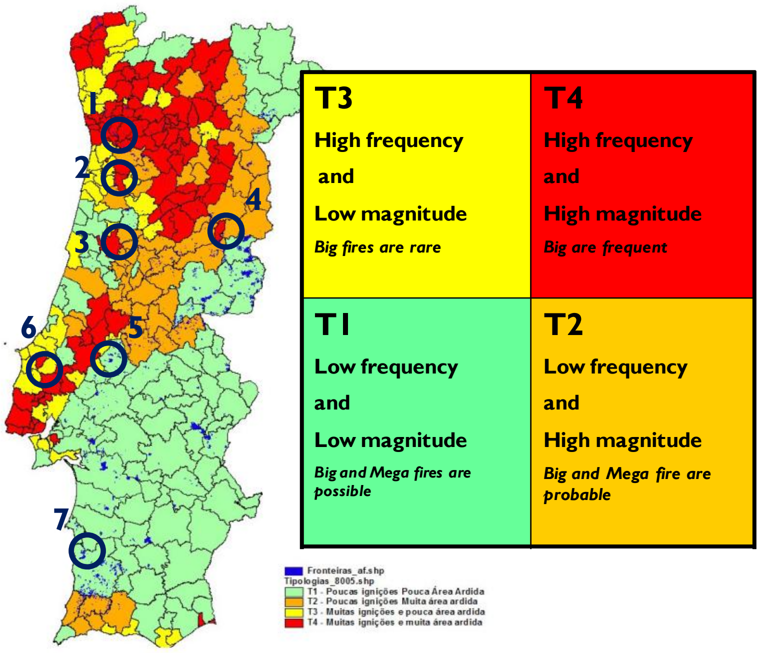

Figure 57. Geographic locations of preliminary case study sites.

Table 4. Description of preliminary case study sites (Oliveira, 2011b).

SITES	Contrasting Fire regimes	Municipalities	Main characteristics	Model complexity	Modeling issues	Stakeholders perspective
1	**Douro Litoral** Mainly T4	Valongo / Paços de Ferreira (zona de paços de sousa) Amarante	Mainly several small propriety of unmanaged eucalyptus stands, abandoned due to fire or other expectation + WUI problem Very fragmented, dynamic and urban + weekend agriculture messy landscape Rugged terrain, high productivity in a high and dispersed density population area	Very high But some strategic fuel treatment prescriptions	*Problem relevance at national level* *Multiple reasons for ignition, fuel accumulation* *Large Amount of data – Complexity* *Multiple cost hard to gather* *Complexity is hard to model*	Forests owner influence + municipalities + active and different fire brigades + state areas *Other project database*
2	**Centro Litoral**	Mortágua / Agueda and others nearby	Proximity to pulp mills, high productivity and low fire risk perception leads small investors to manage eucalyptus stands Homogeneous and very dynamic small private eucalyptus plantations Rugged terrain, high productivity in a average concentrated density population area	High	Pulp Mills strategic relevance Municipality and landowner commitment	Abastena + municipalities + local economics depend on forestry
3 and 4	**Centro Interior** T1 and T2/T4	Lousa/Gois Penamacor / Fundão	Average productivity, bigger properties, homogenous and low fire risk perception leads small investors to manage eucalyptus stands. Small to medium size patches landscape, Pine forest land use in peril by Nematode disease + rural abandonment + depopulation Rugged terrain, high productivity in an average to low concentrated density population area	High to Medium	Pulp Mills strategic relevance Homogenous land use Conservation values *Multiple values hard to gather*	Forest culture + municipalities + conservation issues State owns some areas
5 and 6	**Vale do Tejo** T1 T3 e T4	Chamusca / Coruche Torres Vedras / Mafra	Average productivity sites, multifunctional and bigger properties with pine, cork and vine or agriculture incomes. Strong agriculture activity with forestry medium mosaic. Rugged terrain, high to medium productivity in high density population area	Medium to High	Municipality and landowner commitment Simple fuel treatment ignition patterns	UNAC + municipalities + large forest owners very involved *Other project database*
7	**Sul** T1 and T3	Odemira / Aljezur	Large private propriety, low productivity, low income, low fire records, Diverse and large patches landscape of eucalyptus, cork oak and umbrella pine. Agriculture in valleys Flat to light rugged terrain, low productivity in low density population	Low to High But some strategic fuel treatment prescriptions	Simplicity of land uses	Conservation issues + municipalities

As shown in Figure 54, the research design for each case includes semi-structured interviewing, secondary data analysis, and archival analysis. Answering both of the research questions comprehensively requires utilization of all three methods.

Interviews will be conducted with a variety of different decision makers from each case, where the purpose of the questioning is to build a body of verbal data around each of the two research questions. Decision makers include officials from regional government authorities, such as civil protection, forest management, environmental protection, and law enforcement. Decision makers also include individual forest owners, representatives from forest owners' associations (collective management bodies of forests), and local stakeholders from the paper and pulp industry, specifically gPS. Time and resource permitting, it may also serve useful to interview individuals not directly affiliated with a forest fire management body, but who have experienced a number of fires during their lifetime. They may offer interesting insight that is not influenced by a large institution.

Collection of secondary data of historical fire events will be carried out for each of the seven cases in order to better characterize regional fire activity. In addition, knowledge of particularly memorable and/or devastating fires will help guide further questioning about historical budgetary decision making and fire and fuel management efforts. The National Forest Authority (AFN) and the National Civil Protection Authority (ANPC) maintain large, accessible databases on forest fires in Portugal. These databases include many data fields, including approximate start time of the fire, its cause (if discernible), duration of burning, total burned area, types and extents of areas burned, and who extinguished the fire, among many other fields.

Collection of information on fire-related budget expenditures will also be collected (if possible). The availability and accessibility of this information depends on the documenting practices of regional authorities and their cooperation with the research team. While interviews with regional authorities should shed some light on budgetary practices, having hard data on year-to-year expenditures, particularly when triangulated with fire data from previous years, will allow objective inference about the fire budget decision process.

Finally, archival analysis of regional fire and fuel management initiatives and laws will be carried out for each case. Case-specific initiatives and programs, as well as records of expenditures on such programs, may offer further insight into the differences across cases concerning forest fire management practices. The following section presents an outline of the case study protocol for Case #1: Valongo and Amarente. Some details specific to Valongo and Amarente are included, but the outline of the protocol will be the same for every case.

Case Study Protocol: Valongo and Amarente

A. Introduction to the Case Study and Purpose of Protocol
    a. Reiteration of hypothesized high-level managerial behavior with regard to forest fires: too much suppression self-reinforces further suppression, undermines fuel management, and leads to larger burned areas in the long-run → implication that fuel management could be useful in mitigating damages from fire
        i. This hypothesis drives the two research questions: (1) how do decision makers respond to bad fire years in terms of fire-related expenditures, and (2) do decision makers believe that fuel management is or could be effective at reducing fire severity?
    b. Framework of the study, i.e. to explore differing management complexity, in terms of physical and social variables, across cases and how this impacts management practices and beliefs (including both suppression and fuel management). Valongo/Amarente has high management complexity: dense

population, high yield forests, wet springs and dry summers, many residences on WUI, fragmented land ownership, many forest owners' associations, heavy influence from pulp and paper industry (specifically gPS), among other variables

c. Role of protocol, namely to improve reliability (standardized agenda)

B. Data Collection Procedures

a. Sites to be visited:
    - i. Valongo Civil Protection Office
        1. Contact: José António gtf.valongo@gmail.com
    - ii. gPS regional forest manager
        1. Contact: João Lé (retrieve information)
    - iii. gPS regional forest technician
        1. Contact: Ricardo Mendes (retrieve information)
    - iv. Forest owners' associations
        1. FORESTIS – Rosário Alves geral@forestis.pt
        2. Others
    - v. Town Hall
        1. Mayor of Valongo/Amarente, deputies, ministers
    - vi. Forest owners, public, others

b. Data Collection Plan
    - i. Semi-structured interviews with above contacts using level 1 questions as defined by Yin (2009) – these questions define the verbal line of inquiry; each interviewee is the unit of data collection.

      Warm-up questions:
        1. What is your background and current profession?
        2. How long have you been involved in the forest fire problem in Portugal and in what different capacities?
        3. Do you have any questions about me or my role in this research?

      To help answer Research Question 1:
        1. What would you say are the major causes contributing to the forest fire problem in Portugal?
        2. Who is in charge of forest fire management here? Generally, what is their strategy for managing fires?
        3. Following a particularly bad fire season, what would you say is the most common response of the decision makers here? Do they spend more or less money on different activities, strategies, or resources?
        4. Do you think the national government responds in a similar or different way?
        5. How do you think forest fire management can be improved here?

      To help answer Research Question 2:
        1. There have been *X* large, severe fires here over the past 30 years. Were you working in your current professional role, or a different role but still involved with forest fire management, during any of these fires? Can you recall them specifically, and do any stand out in your mind?
        2. In your opinion, what were the major causes of that/these fires?

        3. Do you think fuel management measures, such as prescribed burning, chemical treatment, or mechanical thinning could have helped prevent the fire(s) or at least diminished their magnitude?
        4. How confident are you in the ability of the forest management agency, or agencies, of the region to carry out fuel management? Do you think they know how to mitigate the risk of fire with these tactics?
        5. In general, how can large, severe fires be prevented in the future here?
    ii. Secondary data analysis of regional fire activity
        1. Fire information
            a. Sources: Ministry of Agriculture (Director General of Forest Resources, National Forest Authority); Ministry of the Interior (National Civil Protection Service); regional data sources (if available)
            b. Data: start time of fires, cause, duration, vegetation types burned, total area burned
            c. Analysis: time series analysis, aggregation across data fields, data visualization
        2. Budget information
            a. Sources: mayors, deputies, regional ministries (others?)
            b. Data: fire management expenditures (including, but not limited to, suppression and fuel management)
            c. Analysis: classification of expenditures (suppression vs. fuel management), triangulation with fire data, preliminary causal inference, time series analysis
    iii. Archival analysis
        1. Regional initiatives
            a. Sources: fuel management programs → consider also including surveillance and detection programs, stricter law enforcement, etc. (not immediately relevant but could still be useful, time and resource permitting)
            b. Data: purpose of initiative, objectives, requirements, measures taken, participation among stakeholders
                i. Can perceptions and beliefs about fuel management be gleaned from the language and implementation (or lack thereof) of these initiatives?
            c. Analysis: coding
        2. Laws
            a. Sources: national and regional
            b. Data: purpose, objectives, language, enforcement, punishment
                i. Are these really enforced? Do people think they are effective? This may lead to follow-up interview questions.
            c. Analysis: coding
c. Expected preparation prior to visit
    i. Review with team before starting each case study

C. Outline of Case Study Report
    a. Regional forest fire management in practice
        i. Before even thinking about the budgetary decision process and beliefs about fuel management, can the management practice be characterized in a simple way?
    b. Innovative or different aspects of management in this region compared to others
    c. Outcomes of the practice; has it been effective thus far? Add here statistics on fire ignitions, burned area, etc. to help quantify the fire situation → do not make causal inferences here, just correlations; preliminary cost-benefit analysis if budget expenditures are available
    d. Fire management agency (agencies) context and the history of the management practice → evolution of regional fire management
    e. Deliverables of case study: chronology of events covering implementation and outcomes of management at this site; preliminary logic model explaining why site favors suppression and/or fuel management in their practice; references to relevant documents; list of persons interviewed

D. Case Study Questions – includes questions addressing both inquiry and evaluation
    a. Level 2 questions as defined by Yin (2009) – guides the mental line of inquiry to develop inference about single case
        i. How have forest fires historically been managed in this region?
        ii. What is the current practice for managing forest fires in this region? Why?
        iii. How is this practice carried out? By whom?
        iv. How is the practice evaluated after each fire season? What are the outcome measures used to evaluate the practice?
        v. What determines changes to current practice, in terms of new laws and budgetary expenditures? Has there been a trend in these changes over time?
        vi. How has the practice for managing forest fires evolved over the past 30 years or so?
        vii. Has the forest fire problem in this region gotten worse or better over the past 30 years or so and why?
    b. Level 3 questions as defined by Yin (2009) – asked across cases in order to develop preliminary theories about why certain fire management practices, in light of answers to the two research questions, occur across regions (case study sites)
        i. Are there practices for forest fire management that are generalizable across all seven cases?
        ii. Are there trends in forest fire-related spending that are similar or different across cases?
        iii. Do certain regions respond differently to the forest fire problem, and for what reasons do they respond differently?
        iv. To what extent are the decision making bodies in each case influenced by national forest fire policy? By the pulp and paper industry?
        v. What are the major drivers of fire suppression-based management? Is it driven by public pressure?
        vi. How and why do fuel management beliefs differ across Portugal?

c. Level 4 and 5 questions asked of entire study, including normative questions about policy recommendations (Yin, 2009) are important but should be posed toward the end of the study

Remarks on Reliability and Validity

The major concern in executing this multiple case study design lies with reliability, and the relative ease with which the case study protocol can be followed across all case study sites. The breadth and depth of this research design will likely warrant the use of multiple researchers, each with individual biases and perceptions of the problem. While the case study protocol can be improved via workshops and meetings with the entire research team, the reality is that each case will present different research challenges along the way. As mentioned previously, access to budgetary information regarding fire-related expenditures will greatly enhance inferential capability around the spending decision process. However, access to this information may only occur in a subset of the cases. Similarly, the information attained from interviewing may vary widely across cases. It may become necessary to trim the number of cases in the study if data and interviews are particularly hard to come by in certain regions. While trimming the number of cases may result in a loss of generality, doing so may also alleviate reliability concerns since fewer researchers (potentially) will be required. Dealing with these obstacles requires that the research team be flexible to changes and also open-minded to new and interesting research directions.

One of the advantages of the case study approach is that the attention to context alleviates many validity concerns. In addition, since the proposed research is exploratory and descriptive in nature, many of the threats to internal validity, as defined by Campbell and Stanley (1963), do not apply. However, the responses of interviewees could be biased given their political affiliations, experience with the fire problem, and personal agenda. Inferences drawn from interview data must therefore consider these potential biases. Characterizing these biases across relevant stakeholders, however, could be an important research opportunity from this design. Finally, the cases were selected in order to minimize external validity threats (they well-represent the spectrum of management challenges in Portugal), but their applicability to other countries is probably limited.

Again based on the exploratory and descriptive nature of the research, it is difficult (and perhaps not useful) to isolate any one construct in need of measurement. At a very high level, this research is searching for evidence of a self-reinforcing managerial phenomenon that leads to perpetual short-term corrections. However, operationalizing indicators to directly measure this phenomenon (or construct if you will) is difficult, and the research questions are phrased such that the answers will help typify this phenomenon across regions qualitatively. To answer these questions, the research design utilizes multiple sources of evidence (interviews, secondary data, archival analysis) in order to investigate regional fire management practice and beliefs. Through coding of interviews and archives, as well as statistical analysis of fire and budget data, a large body of evidence will be available to (1) characterize regional decision making processes around fire management expenditure, and (2) characterize the beliefs about the usefulness of fuel management across regions. Analyzing this body of evidence is discussed briefly in the following section.

Data Analysis

Quantitative and qualitative methods will be used to analyze collected data. Numerous techniques for statistical analysis and data visualization are available to describe regional fire activity across the cases. These include primarily time series analysis and aggregation across various data fields. These data will serve a descriptive purpose by characterizing fire activity, at the very least in terms of ignition and burned area, across the sites.

Budget information will be analyzed and categorized in a similar way. When considering budget information together with fire information, time becomes an important variable. In particular, correlations between fire damage indicators (e.g. ignitions, burned area, cause of fire) will be correlated with fire-related expenditures (e.g. suppression, detection, fuel management) in one, two, three, and perhaps additional years following the damages. The objective here is to see if there is an association between fire damages and fire expenditures broadly, with more advanced clustering and time series techniques also being utilized to establish links between specific fire indicators and budget responses. For instance, what is the correlation between total burned area in year 1 and suppression expenditures in year 2? As mentioned previously, the belief among many fire experts in Portugal is that bad fire years lead to additional expenditures on suppression; quantitative data analysis of the proposed secondary data sources will explore this hypothesis more rigorously and therefore help answer the first research question in an objective way.

Qualitative analysis will be used to measure beliefs about fuel management within the collective decision making bodies of each case. Effectiveness of fuel management is a difficult concept to measure whether by qualitative or quantitative means. Quantitatively, it is very difficult to isolate that a specific fuel treatment led to a certain number of reduced fires or burned area. Meteorological variability, uncertainty around spatial ignition patterns, and a host of other confounding factors are very hard to control for when building this causal relationship. Therefore, beliefs about fuel management will be qualitatively analyzed by coding interview responses and the content of regional initiatives (provided they are written into record) and laws.

A preliminary coding scheme of interview responses will include binary (yes or no) categorizations across the following dimensions of fuel management beliefs: acceptability of the practice, trust in administering agency, and perceived effectiveness at reducing impacts of forest fire. These broad dimensions were largely informed by Toman et al. (2011). They may be further decomposed into more specific measures of beliefs (e.g. acceptability of prescribed fire vs. chemical treatment vs. mechanical thinning) and include further categorizations over simply binary (e.g. a lot of trust in administering agency, some trust, no trust), but these decompositions will depend on the richness of the interview data attained. The basic coding scheme will be tested on a pilot case study (likely Case #1: Valongo and Amarente) to evaluate its preliminary usefulness and potential needs for improvement.

The coding involved with archival analysis is currently difficult to predict. In preliminary discussion with Tiago, it appears that at least one of the cases (Case #2: Mortágua and Agueda) has carried out a regional fuel management initiative, but the content is unknown, as is the extent to which other regions have developed their own initiatives. Investigating whether such archives exist across cases is therefore purely for exploratory purposes.

Conclusion

This research plan seeks to characterize contextual differences in forest fire management across regions in Portugal by answering the following two questions:

1. How do relevant decision making bodies in Portugal respond to bad fire years in terms of expenditures to suppression versus fuel management?
2. Do these decision making bodies believe that fuel management could be used to reduce the severity of large, intense fires in Portugal?

Answering these questions will help shed light on the potential existence of the hypothesized trap of self-reinforcing suppression-based management in Portugal. By exploring different cases, results will indicate the extent to which this trap, and current management practice in general, impacts the regional forest fire problem.

In general, this research will produce a large body of qualitative data about regional budgetary decision making processes and beliefs about fuel management. This information will describe forest fire management practices across physically and socially diverse regions in Portugal. After extensive search of the literature, it appears that this type of qualitative investigation has not been carried out in Portugal. The descriptive contribution of the research therefore fills a major gap in knowledge about regional forest fire management in Portugal.

Another important contribution comes from developing cross-case theory about why regions implement certain policies and initiatives, and why people hold certain beliefs about fuel management. While this is not the primary objective of the proposed research plan, inferences may be drawn if there is sufficient data across all seven cases. This is important because many national authorities in forest fire management in Portugal already have preconceived ideas of what causes the fire problem across the country. Thus, potentially new and interesting theories explaining the problem, specifically ones that pay attention to context and regional irregularities, may help reorient the national policy discussion.

Finally, results from this research plan can help inform and improve the quantitative SD models developed in this thesis. Indeed, Weiss (1995) states that one of the reasons to conduct qualitative interviewing is to identify variables and frame hypotheses for quantitative research. Quantitative models will be useful for explaining to decision makers at regional and national government what the effects of different policies are on improving or worsening the forest fire problem. While the case study research is exploratory and descriptive in nature, the quantitative models can serve an explanatory purpose, and therefore potentially prescribe efficacious policies. In this way, the proposed qualitative research will be useful for enriching the already developed quantitative models with necessary contextual detail.

Appendix E: Rekindle Mitigation Project

This appendix outlines a rekindle mitigation project for grupo Portucel Soporcel (gPS). As mentioned before, gPS is one of the largest pulp and paper companies in Portugal and is one of the project collaborators in FIRE-ENGINE. In order to protect their forest properties from fire, gPS contracts out fire suppression responsibility to a company called Afocelca (Afocelca also carries out fire suppression for the other major pulp and paper company in Portugal, Altri). The purpose of Afocelca is to centralize fire prevention and firefighting activities, and as a group they tackle more than 1,500 fires per year of which 85% are in neighboring properties to gPS land (gPS, 2009).

The rekindle mitigation project will function as a demonstration of the policy implications of the operational SD model, namely that longer suppression time targets result in fewer rekindles. gPS and Afocelca are uniquely poised to develop such a test bed for policy changes to fire suppression because they are in the private sector. As was mentioned previously, the people in Portugal have a certain expectation about the expediency with which fires will be extinguished on or near their property. A mandate by the federal government that fire suppression forces must spend more time at each fire such that all opportunity for rekindle is prevented will likely not garner public support despite the good intentions. On the other hand, a private sector player like gPS has more leeway since they have their own fire suppression force (Afocelca) and only one major group of stakeholders that needs convincing, the shareholders.

While there are certainly limitations to the operational SD model developed in this research, the basic logic governing the relationships between variables is reasonable, which makes the output of the model an important basis for discussion. If fire managers for Afocelca believe that some concept of pressure mounts on the firefighters as ignitions increase, *and* that this pressure may lead to insufficient mop-ups or premature departures, then the model gains credence. Nonetheless, with support and leadership from gPS, Afocelca can test the impact of different policy changes on rekindle incidence.

The results from the operational model suggest that a longer suppression time target may reduce rekindles. However, setting up controlled experiments to test longer targets against the 90-minute standard would be challenging. Despite the simplicity of the operational model, there are still numerous variables in the causal chain that if not held constant may threaten the internal validity of the experiment (e.g. ignition rate, net resources, productivity of crews). To be sure, there are other variables not modeled explicitly that would also need to be controlled for, such as vegetation types, distance to fires, among many others.

Instead of attempting to do controlled experiments, it may be more useful for gPS to observe the general performance of a pilot policy implemented during one summer that combines a longer suppression time target with a more comprehensive policy that suppresses fires in a systematic and thorough way. This would include requiring complete mop-up with hand tools after extinguishing each fire, a process that naturally takes more time but may be easier to facilitate if crews aren't encouraged to extinguish fires as quickly as possible. To get the most out of the pilot policy, fire managers would need to take an active role in observing how the policy change affects crew motivation, morale, and overall performance. This data, even if qualitative or anecdotal in nature, is important for evaluating the social effects, namely the effect on workers, of institutional policy changes. Afocelca collects an immense amount of data each fire season at their central command center in Figueira da Foz, including information on rekindles as of 2010. Changes in the number and severity of rekindles, i.e. the physical effects of the policy change, could then be combined with manager observation in order to get a preliminary idea of how the socio-physical dynamics are changing under the new policy. While the purpose of this demonstration project is ultimately to mitigate rekindles, in some ways a more important, though subtle, objective is to simply gather information, at both the crew and central command level, in order to iterate and improve on current practice.

The project described thus far essentially seeks to make Afocelca's suppression system more efficient, better protecting gPS properties and profits. While instituting a pilot policy study would require little upfront cost, gPS may be loath to take the risk on a new and unfamiliar policy. After all, a policy change aimed at fixing one unintended consequence may itself create another, and so on and so forth. Nonetheless, each new solution brings deeper awareness to the underlying causality of the problem, which in turn leads to the discovery of increasingly systemic and comprehensive solutions. Thus, by spearheading a project to tackle the rekindle problem, gPS conveys to the public that it is taking an innovative and holistic approach to forest fire management, setting an example for the national leadership that has suffered from a narrow focus on forest fire problems in general.