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Forest Fire

Edited by Janusz Szmyt

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Meet the editor

Janusz Szmyt is an adjunct at the Silviculture Department Faculty of Forestry at the Poznan University of Life Sciences, Poland. He earned his MSc and PhD degrees in silviculture at Poznan University of Life Sciences. His scientific interest focuses on different aspects of forestry and forest ecology, e.g. forest dynamics and the influence of natural processes on forest dynamics, regeneration and tending operations in immature forest stands of different origin, the influence of initial density of regeneration on forest stand growth and development, different methods of stand regeneration, forest plantations, afforestation of agricultural lands after their agriculture use, forest conservation, forest management and forest succession after the natural disturbances. In his scientific project, he is interested especially in the application of spatial statistics in forestry. His current research project is focused on the influence of different management systems on structural diversity of Scots pine stands.

Contents

Preface

In the changing world, among other environmental conditions, it seems necessary to get knowledge about the impact of climate change related to global warming on forest ecosystems. One of the factors exerting a clear influence on forest cover in the world is forest fires. On each continent, an increase in the number of fires is observed as well. The reason for the increase of forest fire hazard in the world is, among others, the climate change.The United States, Russia, Canada, European countries as well as South America are nowadays especially vulnerable to the occurrence of large-scale forest fires. To imagine the scale of the problem, we can quote a number corresponding to the loss in the forest area equal to the area of New Zealand. This number applies only to 2016.

Forest fires, in addition to causing losses in the natural environment and natural resources, also generate higher social costs related to prevention, rescue actions, compensation payments as well as costs of activities resulting in changes in the use of natural resources. Worldwide, forest fires are caused both by man and by forces of nature themselves (e.g. lightning). Therefore, it is likely that in the near future, forests and societies will face a great challenge related to the forest protection against fires.

In this book, the reader will find information on various factors related to forest fires. In one of the chapters, the reader will be able to find out how the profile of a potential arsonist can be made; in the next one, he will learn about potential social conflicts resulting from the current use of natural resources and related forest fires by the local communities and how to resolve these conflicts. The reader will also learn about techniques of forest fire detection using new technologies; he will learn how to use forest fire modelling techniques to properly reduce their adverse effects.

Many people deserve hearty thanks for bringing this book to reality. In particular, I would like to thank all the authors who contributed to this book. Special thanks go to Marina Dusevic from InTech, who patiently guided me through the project and reminded of crucial dates related to preparation of this book. It is clear to me that without her help, this project would not have come to the end. Finally, I thank my colleagues for their inspiration and support. At last, but of course not least, I would thank Karolina, who makes my work nice and easy.

Thank you all.

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Section 1

Forest Fires - Social Conflicts and Causes

Chapter 1

Ruling Frameworks and Fire Use-Conflicts in Tropical Forests of Chiapas, Mexico: A Discourse Analysis

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Additional information is available at the end of the chapter

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Abstract

The use of fire within tropical forests to settle agriculture and livestock systems has long been causing a bottle-neck for governmental and environmental development agencies, especially in natural forested areas with local population. An international strategy followed since many years ago is the decree of special territories with vast forests as natural protected areas (NPA). In Mexico, environmental laws can run contrary to customs and practices of natural resource-dependent communities which still use fire to farm their lands as unique livelihood activity. The chapter examines two conflicting frameworks of resource management (forest and soil) and governance in a forest village's efforts to comply with federal policies against fires in a NPA of Chiapas, Mexico. Forest and soil management is a key *locus* in California village, where governance structures come into conflict with hierarchical State power. Participatory workshops and semi-structured interviews were primary research instruments for data collection and discovery of community front and backstage. Ethnography and discourse analysis were used as main tools for the analysis of information. While the State leads the conservation efforts and limits cultural activities and local actions through coercive laws, the land use and resource-dependent communities defend their access rights, and they also determine how to individual or collectively manage fires in daily activities. Finding collective solutions with horizontal-dialogue strategies represent an important issue and a pending task for the development and preservation agencies focused on forested areas. Backstage dialogue is a tool for village self-preservation when livelihood strategies are at odds with protectionist conservation efforts.

Keywords: conflict management, biodiversity, governance, customary laws, farming styles

1. Introduction

Mexico is considered to be one of the most biologically diverse countries in the world, with 10–12% of the world's known species [1]. Since the 1970s, creation of natural protected areas (NPAs) has increased as a conservation strategy, and these biodiversity "reserves" now cover nearly 13% of the country's land surface [2]. NPAs are designed to implicate the participation of several actors from the public and private spheres, including federal agencies, government-contracted biologists, nongovernmental organizations involved in agricultural extension services, and local communities. By means of the participation of each, the actors are expected to foment conservation and alternative use of natural resources [3, 4]. Nearly, 60% of Mexico's NPA surface is within the United Nations' "Man and the Biosphere Program[1]" reserve category, making these federal reserves the country's most important NPA category [2]. Governance of biosphere reserves has been a challenge, due to the immense diversity of agroecoogical conditions, evolving cultural practices, and agrarian pressures that are found in such places, as well as the multijurisdictional, complex nature of conservation planning and implementation in Mexico.

Like all of Mesoamerica, southern Mexico has millennial traditions of agriculture, often based on shifting fields and the periodic use of fire. Tropical ecosystems store most of their nutrients in plant matter, rather than the soil, so for centuries indigenous farmers used to burn areas of forest in order to create fertile beds of ash. On these fertile beds, new crops and native grasses can be grown for a few years, while adjacent fields are left to regenerate. Known as *slash-and-burn* or *swidden agriculture*, these indigenous systems are still being practiced today.

The use of fire within agriculture systems has long provoked the ire of governmental development agencies in many countries, which seek to replace them with permanent field agriculture [5]. Swidden agriculture was opposed during the Green Revolution years in Mexico for its purported

[1]The Man and the Biosphere (MAB) Program is an intergovernmental scientific program aiming to set a scientific basis for the improvement of the relationships between people and their environment globally [8].

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low productivity, while more recently it has been called environmentally destructive, often without consideration of its complex ecological bases [6, 7]. In addition, the growing evidence of climate change, such as recent severe droughts, is another important element feeding the external as well as internal discussions on traditional fire practices. The argument about climate change, in combination with major forest fires in the 1990s, as well as increasing population pressure on land resources, made peasant fire use a target for environmental regulation in Mexico. Mexican federal regulation generally seeks to prevent the practice, without offering a clear alternative for agrarian communities.

In Mexico's southernmost state of Chiapas, many rural communities rely on *usos y costumbres* (customary laws)—rules based on unwritten tradition and typically used only in much older communities—to provide the legal and political framework for governing daily life and managing conflicts. These diverse and often unwritten codes also guide community processes of adaptation to change, such as the kinds of restrictions put in place by nature reserves [9]. In the case of fire use by communities, federal environmental law and NPA rules generally seek to prevent the practice, without offering a clear alternative for agrarian communities. Official governmental regulation therefore sometimes comes into conflict with *usos y costumbres*, leading to tension between local communities and government officials.

In order to better understand the internal processes that guide communities' use of fire, as well as the tensions between federal rules and local *usos y costumbres*, a long-term research was carried out on the political and social dynamics of the peasant village of California in the Sepultura[2] Biosphere Reserve of southwestern Chiapas, where the local community is at odds with federal environmental management agencies.

2. Methodology

2.1. Regional and social context

California is located in the Frailesca region of Chiapas. The region is made up of valleys and plains dominated by monoculture maize fields with Green Revolution technologies, surrounded by mountainous zones where traditional farming methods are practiced by small communities. Near the region's major city, Villaflores, the School of Agronomic Sciences from the Autonomous University of Chiapas (UNACH) sits up against the foothills of the imposing Sepultura range. As part of the research and extension services offered by the university, a research team[3] was formed in 2003 and later on in 2014 to conduct fieldwork in small settlements of the Sepultura Biosphere Reserve. It was planned to examine among other things, why (a) the use of fire is a sensitive social issue in the villages; (b) basic grain production was losing importance in the region, and (c) to promote farmer innovation toward more sustainable

[2] *Sepultura* means "tomb" in Spanish.

[3] The research team consisted of four professors and six to ten BSc and MSc.degree students from the universities of Chapingo, Chiapas, and Wageningen.

technologies. For a period of 6 years, the researchers visited the village on a regularly basis, gathering data and providing extension services. This chapter focuses only on the research aspects of the process carried out.

A major challenge for agronomy and agricultural sciences is to break out of top-down, traditional extension model and to embrace more horizontal, participatory research models. A necessary part of this transition is to make researchers and students sensible to the cultural diversity in rural communities, recognize local knowledge, and promote a "dialog between differing knowledge systems." Rural researchers in Latin America who embrace these needed changes often follow the tradition of participatory action research as suggested by the Mexican agronomist Efraim Hernández-Xolocotzi [10] and Colombian sociologist Orlando Fals-Borda [11], as well as the educational work of Brazilian pedagogue Paulo Freire [12, 13]. Participatory action research, also built on the thinking of these authors, with its emphasis on the creation of spaces for reflection and dialog in the village, guided this research in California.

The methodology used in this research was developed as an innovative mix of two approaches: action-oriented and ethnographic (socio-anthropological) research methods as suggested by [9]. An action-oriented approach was assumed looking for the village's inclusion as part of the research process, particularly for the discovery and reconstruction of historical moments and the sharing, reflection, and negotiation of factual information. Villagers were seen as more than passive participants and took an active role in all the field work undertaken. Thus, the action-oriented methodology relied on a participatory action research (PAR) perspective. Then, at least a learning cycle through action was run, while the stimulation of collective reflections during the workshop implementation was encouraged. According to [9, 14, 15] by using a PAR perspective, at least six important contributions are done: (1) the stimulation of a collective learning process while acting on investigated topics, (2) the achievement of worthwhile outputs beyond the specific research interest, (3) engagement of participants in a collective learning reflection process, (4) bringing out local inertias as topics to think about, (5) bridging the gap between researchers and the researched, and (6) challenging current research paradigms. In this sense, the research team came in and out of the village during two periods, in 2003–2007 and 2014–2016 (**Figure 1**).

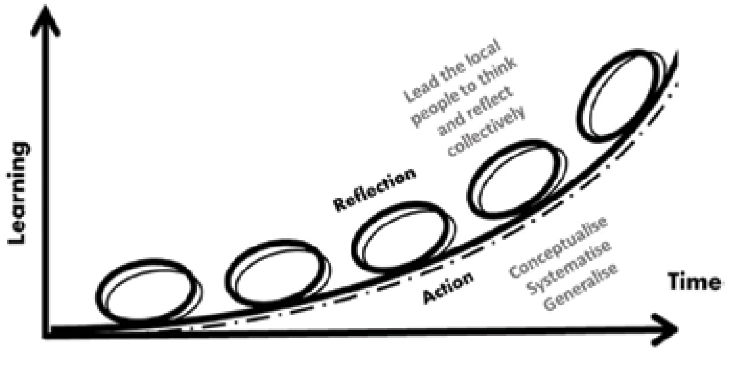

Figure 1. Action and research cycles in participatory action research. (*Source*: Modified from [14]).

From the outset, relationships between the inhabitants and outsiders were clearly conditioned by the history of the village's complex interactions with municipal and federal authorities as it fought for recognition as an *ejido*.[4] As it became clear in the beginning of the research that certain frustrations and doubts deeply held by the village were not explicit in public settings, researchers felt the necessity to start using ethnographic methods during the first months of fieldwork [16]. In addition to participatory research, ethnographic methods have become a respected element of community-oriented research, due to their capacity for bringing together many accounts of daily life "as seen from below" into coherent narratives to reveal a sociocultural reality often overlooked by conventional expert-based research methods [17, 18].

During 2003–2007 and later on from 2014 to 2016, six participatory workshops of 3 days each for every research period were conducted. During the workshops, a collective timeline was built, and topics such as the economy, production, the village's relationship with the Sepultura Biosphere Reserve, and other local issues were discussed. In addition to the workshops, researchers conducted a total of 240 interviews over the course of the fieldwork, including women and men, elders, and youth. The semi-structured interview was employed, allowing interviewees to speak about the issues they pleased, although researchers returned to certain specific questions in order to guide the conversation [19]. Questions are related to a wide array of California, agricultural, and environmental issues, including the history and conflicts concerning fire use by residents.

In the coming sections, a reflection on a series of action research and ethnographic findings in both research periods in relation to a long-term confrontation California had with federal government agencies' rules with regard to traditional fire use in the forested area to settle traditional farming systems is drawn. Narratives and discourse analysis as main tools for the analysis of information are used to describe the context and village discourses on fire use, confrontations, and negotiations on the use of local natural resources in California. Peoples' names have been changed in order to protect their privacy.

3. Results

3.1. Updating on current conditions of California village

The Pacific coast of Chiapas practically runs east-west, bordering Oaxaca on the west and Guatemala on the east side. The *ejido* or village called California is the second highest in elevation of a string of communities along a fast-moving river that flows from the heights of the western Sierra Madre mountain range into the coastal plains to the south. The highest location, Tres Picos, is named after the mountain it sits under. California and its downstream neighbor, Los Angeles, were so baptized as humorous tributes by migrants returning from the United States.

California is built on a flat area of a high-altitude tropical forest with about 2550 mm annual rainfall and an elevation of 1500 m a.s.l. Rainfall generally occurs in the period of May until

[4] *Ejido* is Spanish for "a sort of collective lands or communal fields" but here also refers to California.

September, often coinciding with the presence of cyclones and tropical storms. The village has in 2017 about 900 residents and is one of several small rural communities in its municipality (**Figure 2**). Most habitants are *mestizos* with substantial Maya ancestry; they have settled from several different regions of Chiapas, making California a culturally diverse settlement.

The 1222 ha of land held by the *ejido* are managed under two systems: individual plots for farming and common property forestlands used for firewood and construction material. Villagers traditionally cultivate maize, as a maize commodity boom in the 1960s led to the creation of an agricultural frontier in the mountains of the Frailesca region, and landless farm workers foresaw the opportunity to farm maize profitably in the highlands [20]. Most residents live primarily as small-scale agriculturists, with maize-bean-squash *milpa*[5] systems covering

Figure 2. Location of California in the municipality of Villaflores, Chiapas (Mexico).

the surrounding hills during much of the year. A small amount of cash crop sorghum and chili pepper is also grown in fields, as well as diverse assortments of fruits, vegetables, and herbs in home gardens. Production is generally for domestic consumption or used to grow livestock, which in turn is the major cash income source to California. The traditional *milpa* production system is increasingly being converted into cattle pasture. Cattle possession is a function of family wealth and a solvent reserve capital for peasant families. Most families have no cattle, but those who do have cattle have between eight and ten cows in nearby fields.

3.2. Recalling the history of California

A social reconstruction of California history took place during the workshops in the first period of the research, in which all sectors of the village were represented, in an assembly room with nearly as many women as men. In total, there were about 30–50 participants in each workshop. Elders had a lead role in the workshops; their explanations of past events were often confirmed by nods and reminders from the rest of the group. During these sessions, the frontstage aspects of California life were apparent: a unifying narrative, the collaboration of all residents present, and the obvious affection between young and old.

California was settled in 1975 as a land occupation by settlers from different parts of Chiapas. Many came from regions of social unrest or zones affected by Chiapas' massive hydroelectric projects. Most of the future residents of California met in the earlier and larger downstream settlement of Los Angeles while working as farm laborers. They learned of a wealthy landowner who had abandoned part of his property in an area nearby. About 20 people met secretly for some months and planned an invasion of the abandoned ranch and forested areas. Following a strategy that was commonly used to access land in southern Mexico during the 1970s and 1980s, they occupied the ranch without warning in spring (1975) and set up plastic shelters under the trees to serve as houses. Between 1975 and 1980, scores of other families joined them, but it was not until 1981 that California began to take on the appearance of a permanent settlement, with the construction of the first wooden houses. In the meantime, settlers planted small areas with crops such as maize, beans, chili peppers, and squash, using machetes, axes, and fires to clear the densely forested land. At the first meeting to create a local assembly in 1980, the settlers collectively claimed 1222 ha of forest for future agricultural and firewood needs. A committee composed of seven elected representatives began regular visits to the Villaflores municipal offices and the local branch of the Ministry of Agrarian Reform (now Ministry of Agrarian, Territory and Urban Development: SEDATU), to negotiate for land use rights and title as a communal settlement or *ejido*. At the meantime, the owner of the former ranch took steps to legally defend his land from the settlers.

3.3. The conflict emerges

After nearly 15 years of negotiations, California was finally recognized as an *ejido* or village and the former owner indemnified by the Mexican government. The official decree and federal

[5] *Milpa* is Spanish for "maize field," but in the past, it was a generalized multi-cropping system of maize, beans, squashes, and chili peppers.

certificate of right holders were personally handed to the *ejido* commissioner by President Ernesto Zedillo (1994–2000) in August 1995. The president made a public act of giving land rights to the residents, and at the same time, he promised federal resources (budgets) for the region, which had been declared a national disaster area after being badly affected by Hurricane Herminia.

President Zedillo's visit in 1995 left California residents with several impressions. The first was that he would support local communities damaged by the hurricane (during his visit, he provided some construction materials to residents to construct new homes). Second, he gave an official blessing to local practices and rights of residents, through the certificates of occupancy he awarded. This gave the settlers the assurance that they held rights to the land they had occupied and settled. However, villagers were unaware that 1 month earlier, Zedillo had decreed the Sepultura Biosphere Reserve, a vast protected area in high forests, which included the territory of some hundreds of small communities, including California [21]. When the reserve was created, official federal rules for resource use in the Sepultura Biosphere Reserve were put into place that were in sharp contrast with the local tradition-based law adopted by the *ejido*.

By adopting *usos y costumbres* (customary law), California settlers had made the decision to determine their own civil and productive protocols. Some of the rules and traditions included the following: individual lands were assigned for cropping and household animals, collective areas for livestock, and forest activities; wood from the reserve is not authorized to be commercialized, and communities do not harvest it to sell; the agricultural and pasture lands have been more or less internally distributed per person; the areas must be rotated in terms of management and can be used again for the same purpose between 6 to 10 years later, according to local rules; the common forest on the mountain hillsides was only to be used according to family needs; and more than half of the forest territory has been kept as natural forest because it is too far for inhabitants to walk there, carry out *milpa* activities, and walk back in a day. Residents had brought fire management skills from various regions of Chiapas and use *ejido* meetings to further define village-level rules for forest management.

Villagers were never directly informed about the presidential decree regarding the nature reserve in which they and their territories were included; instead, they simply noticed the construction of a permanent encampment of the National Commission for Natural Protected Areas (CONANP for its acronym in Spanish) 1 km from the village in early 1996. Then, officers from CONANP sent invitations to authorities from California, Tres Picos, and Los Angeles *ejidos* for a series of informative meetings about the nature reserve. The meetings were meant to explain the reasons and implications for decreeing a nature reserve and the justification for building the encampment. Residents who attended these meetings were expected to inform the village about the creation of the reserve, but not directly participate in the planning of the reserve or give feedback to authorities. Their role was reduced to signing a document that officers showed them. Vicente, an elder resident present at those meetings, said: "The officers started their dialogs by saying how nice the region was, the natural scenery beauty, and their duties as part of a federal institution. They approached us with informal ease, even without knowing anything about California or us. That was the first time we had ever seen them."

Then, Francisco, one of the original California settlers, recounted: "As soon as they did not see the reaction they wanted from us, they changed their word choice and demeanor, and began to talk about sanctions as a way to threaten us. I think they tried to intimidate us. We were sure we weren't breaking any law at all but they highlighted all the consequences, if we were to do so." After two or three meetings, the officers vanished, until an anti-fire brigade came to extinguish a fire in a nearby *ejido*.

A brochure distributed among the communities of the reserve after the CONANP officers' meetings stated a series of new restrictions on land use like (i) penalties for and restrictions on the use of fire in agricultural and cattle-rearing activities, (ii) intensification of agricultural areas despite of shifting cultivation, (iii) prohibition of cattle-grazing within forest areas, (iv) prohibition of wildlife hunting, and (v) prohibition on tree-cutting and any wood extraction from the nature reserve without official permission from the CONANP or authorization by the Federal Environmental Protection Agency (PROFEPA in Spanish). Because these restrictions fundamentally altered the relationship of residents to their legal territory, villagers and their representatives have grappled ever since with how to continue to live on their land without openly defying authorities.

Federal agencies seemed to withhold information from the village, arousing deep distrust. Rubén, a man in his 30s, summarized a common sentiment: *"…Actually, the nature reserve represents a burden for us. We assume the good intentions behind the area, but what about us? Are we considered to be part of or just an obstacle to the officers' objectives? We want to hear truthful accounts and realistic proposals for the reserve, rather than just prohibiting things and looking at it as an untouchable area."*

3.4. Fire use and its farming reasons

Periodic fire use is an important element of indigenous rotating field agriculture in Mesoamerica, as in many tropical regions around the world. In California, the rotation includes (1) a 1- or 2-year *milpa* phase, in which fields are planted with maize and several other plant crops, including squash, pumpkin, tomato, watermelon, chili pepper, *chipilín*, and several kinds of beans; (2) an intermediate *acahual*[6] *bajo* phase in which fields are left to ecological succession, and only perennial plants such as chili and *chipilín* are harvested from the former *milpa* during 1 year; (3) a 6- to 20-year *acahual alto* phase in which fields regenerate into diverse forests of native trees and form habitats for migrating mammals, birds, and reptiles; (4) finally, most trees are harvested for timber (although several species are left standing), brush is chopped low, and the leveled plant debris is burned according to local custom—direction of the wind, the humidity, and the manual establishment of a fire perimeter prior to burning are part of this custom—to leave a rich layer of ash over fields. Into this ash, maize seeds are sown, and the cycle begins anew.

The dry coastal side of the Sepultura range has been highly susceptible to seasonal forest fires for decades. High temperatures and low humidity from December to May, as well as periodic

[6] *Acahual* is Spanish for "secondary vegetation," a stage of natural forest regeneration.

strong coastal winds, together create high-risk fire conditions. In 1998, thousands of forest fires broke out across Mexico, including parts of the Sepultura Biosphere Reserve [22]. Especially, disturbing was the fact that forest fires were found in ecosystem types where they had not previously been reported, as well as the areas more traditionally prone to fire [23]. While the 1998 forest fires were attributed to a particularly long dry season, international bodies and neighboring countries accused the Mexican government of having inadequate policies on fire prevention [24, 25]. In response, the government of President Zedillo declared that agricultural activities were the main cause of forest fires and launched the Program for Productive Conversion of Slash-and-Burn Areas,[7] a national fast-track program to replace the use of fire in agriculture, ostensibly with green manure and cover crop technologies. In practice, however, this program has consisted in the replacement of traditional *milpa* production system with permanent-field monoculture maize (requiring intensive use of synthetic fertilizers) or other crops such as greenhouse tomatoes or the community-level replacement of agriculture with conservation payments [26].

After 1998, the Sepultura Biosphere Reserve adopted a general policy of fire suppression, including the initiation of pilot programs of Integrated Fire Management in two communities of the Reserve [23]. At the village level, this fire suppression policy has confused maize farmers who had no alternative food system to replace their swidden agriculture. State and federal policies have made communities increasingly dependent on periodic cash payments and programs.[8] These cash transfers, combined with the fire suppression policy, have the net result of making agrarian communities more dependent on purchased food [27]. At the same time, some program's offerings such as fertilizers and herbicides, where handed out without any training on their safe and efficient use. Among peasants who had never used external inputs, this led to accumulation of the agrochemicals in their houses or experimental usage.

The Reserve's explicit vision of permanent-field agriculture surrounded by areas of conserved forest coincides with the increased use of agrochemicals, as the soil's natural fertility declines under the pressure of monoculture production and chemical inputs replace ecological processes. The health effects of these agricultural intensification processes in Chiapas peasant agriculture are often identified by farmers and researchers as serious concerns [28]. Additionally, the ecological soundness of biodiversity conservation strategies based on patches of wilderness reserves surrounded by intensified agricultural landscapes has come increasingly into doubt [29].

3.5. Highlighting the conflict: the fire backstage

In California, public display or frontstage image serves to recall shared concerns and codes of conduct. Yet, public display is only one side of village life—uncertainty, disagreement, and negotiation are also an intrinsic part of community life [30, 31]. Therefore, researchers decided

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[7] *Programa de Reconversión Productiva de las Áreas de Roza-Tumba-Quema*

[8] Government programs such as *Prospera* (which pays mothers whose children attend school), *Procampo or Proagro productivo* (which pays about $80 a year to farmers for each hectare of land that was planted with maize at the time the program started in the 1990s), and *Amanecer* (monthly payments to elders over 65 years old)

to employ ethnographic methods in order to develop a fuller understanding of the collective narrative, as well as inner tensions among the California residents.

During the first months of fieldwork, inhabitants talked openly about general problems during the workshops conducted in order to delineate the collective narrative of California. However, they felt uncomfortable talking about any "legal situation." Further workshops then revealed tension among villagers, essentially related to an economic sanction issued to California by the PROFEPA. While conducting the participatory workshops, some participants insisted on discussing the issue, and some residents took strong positions regarding the cause of the problem. In certain occasion, a workshop became highly emotional, and some aggressive statements were made. In that sense, Cesar raised a position clearly: *"It is right, our legal problem is something that is affecting our cohabitation as inhabitants, it is actually not an ejido [collective] problem, but it is due to the actions of careless people. We know who they are -they are the responsible of the penalty- and they do have name and surnames…"*

The meeting immediately became tense, as villagers absorbed the significance of Cesar's denunciation. Another participant, Tomás, reacted to Cesar's statement by saying *"That is false; a penalty was imposed on the ejido, not on some specific people. What you say had happened when a resident was caught, but later on he was imprisoned and also had to pay a fine; but that is already history."* When it became clear that there were different perspectives on the issue, the unspoken tension clouded the meeting, and researchers noted that they have spoken to in a more formal manner than in comparison with before the antecedent. The researchers therefore decided to avoid bringing up the fire issue in public spaces but instead used interviews to listen to residents' perspectives on fire.

Days after the first meeting that revealed internal tensions in California, several villagers approached researchers with apologies and explanations for what had taken place. Semi-structured interviews showed that while residents held differing opinions on a variety of issues, they preferred that researchers should not delve directly into those issues. Carlos, in his 30s, made a direct suggestion to researchers: *"From now on, you and I are building a friendship and we can talk about whatever you like. But please, while in California do not talk about sensitive issues to anyone; be careful of approaching the right people, just to protect yourself and colleagues."*

Francisco also said: *"I need to be careful of what I point out: the less I talk, the fewer problems I acquire. I am a very honest person, and I want to keep my life in that line. I always act in relation to what I think it must be. I respect everybody; especially since we were at risk of losing our lives during the village foundation process…"* He defended the firefighting record of *ejido* authorities. *"The only thing I can tell you about the PROFEPA fine is that the fire we used on our fields jumped over to an area within the natural protected area and about 10 ha of forest were burned… I normally say what I know, but you better talk to the Ejido Commissioner because he may have better and more current information."*

The participatory workshops had provided a forum for the village to discuss the issue, but evidently it had been decided to withhold debate in such a visible setting. Residents repeatedly asked researchers if they had spoken with other key local figures, such as the *ejido* commissioner or certain elders. The interest in defusing the tension surrounding the fire and the

PROFEPA fine was clear, but villagers needed confirmation that researchers could be included in backstage conversations. As researchers began to relate elements of previous conversations they had sustained with *ejido* elders and better understand what had happened, interviewees became much more open. During the interviews, they seemed more willing to provide their opinion and retrace the events that had led to the tension with federal agencies.

3.6. Deeper into the conflict

After the creation of the nature reserve, residents decided to continue fire use within the forested areas for agricultural purposes, despite the threat of fines and jail time. Thus, it occurred that in April 2000, the driest month of the year, a first accident occurred, during an urban—rather than agricultural—use of fire. Residents had collectively decided to clear the areas around houses by slashing and burning for sanitary and safety reasons. They justified the use of fire because of the high incidence of mosquitos, as well as venomous scorpions and snakes. Suddenly, while burning, the wind changed direction and the blaze caught nearby trees on fire. About 1 ha of forest was burned, but due to the fire's brevity and limited affected area, residents did not consider possible consequences.

Eduardo explained *"We did not deliberately set fire to the forest; we just tried to protect our families. The wind moved suddenly to another direction and a spark jumped out of the fire area into the forest. We tried to combat it but unfortunately a hectare was totally burned. We tried our best but authorities punished us."* However, forest guards and rangers from CONANP were surrounding and immediately noticed the fire by the smoke presence. When they arrived to California, the fire was already extinguished. Nonetheless, after some brief talks to some villagers, they were gone. Surprisingly, after a month, the government of Villaflores municipality requested the *ejido* authorities' presence at their headquarters.

The municipal staff informed village authorities of a federal sanction of US $2000 to be fined to the village. The *ejido* commissioner attempted to clarify the situation, but the staff argued that any claim or cancelation was not their duty, because the fine was decided by PROFEPA, the federal agency for environmental protection. The village authorities returned to California and convened to an immediate *ejido* meeting in order to inform residents and decide on the next steps. As Vicente recalled, the assembly decided that *"the fine should not be paid because California did what it could, not only to protect its population but also in terms of fire management. The fire was an accident."* The local authorities traveled back to the municipality some days later and expressed their position, verbally and in writing. To avoid problems between *ejido*, municipality, and federal institutions, the municipal staff negotiated with the PROFEPA and the CONANP officers and conciliated an agreement: the municipality would cover 10% of the sanction, but at the same time, an effort to run a reforestation plant in the affected zone had to be made. Then, the municipality proposed a series of activities within its agricultural development plan to be implemented. Thus, several young tropical trees and coffee plants were planted in the zone during 2001–2002. Nevertheless, California villagers were never told about the agreement between PROFEPA and the CONANP officers and the municipality staff—besides, none of the *ejido* officials were notified of the negotiations.

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In 2002, a second accident occurred. Some inhabitants continued to use fire in order to rejuvenate grass fields, despite efforts made by the authorities to stop this traditional practice. On one occasion, two young men who wanted to stimulate grass growth for their cow herds lost control over a fire in a commonly held forest area. Sparks jumped and more than 10 ha of prairie burned, killing a few cows and burning down several nearby trees. The two men were arrested by *ejido* police and forced to pay damages according to local assessments and decisions made by the village assembly. In the local *usos y costumbres* system of justice, the offenders were forced to pay for lost grass and cows, but were not fined for burned trees. However, within a short period of time, officers from PROFEPA came and arrested the men, charging them a fine for the lost trees. The two persons were not able to pay and were forced to serve 3 months in jail. They were later released through the effort of *ejido* authorities but had to sign a document in which they promised not to use fire anymore for their agricultural activities.

Vicente, the representative of the *ejido* to the municipality at the time, was upset that the village's internal justice system had not been respected by federal authorities: *"They must go to the jail once a month and sign in as parolees; otherwise they can be re-arrested. They do not even know when they will be totally free."* He felt that California was capable of punishing them adequately for their mistake and bringing them back into the fold as normal villagers.

A third uncontrolled fire took place in May 2003, during one of the first participatory workshops conducted as part of this research. During the session, a number of children came in and alerted their parents that they had seen smoke and flames. Rapidly, the workshop participants left the hall and mixed with others who had come out of their houses. Eduardo, the *ejido* commissioner, became furious and addressed researchers: *"You see what really happens in this village, here there are still many irresponsible persons but we will punish them."* After 3 h of intensive work by more than 70 inhabitants, the fire in a 3-ha forest plot was controlled. Nobody was arrested that day by the *ejido* police. Two days later, the researchers were politely asked by Eduardo to leave California for some days in order to let him resolve the problem. A couple of weeks later, the researchers were welcomed back by the local authorities. They had completed an investigation and determined that the teenage son of a *milpa* farmer had started the blaze. He would be sentenced to carry out several periods of unpaid labor to the village, which local authorities would define on a weekly basis. California leaders had attempted to avoid penalties by PROFEPA by saying that no one had seen anyone start the fire, but officers did not believe the story and considered the *ejido* to be uncooperative.

What occurs in California's backstage plays a crucial role in local political processes, particularly for the collective management of natural resources. The third fire accident put village leaders on the defensive setup, after they had worked to show that they could manage fire without federal fines, municipal officers, and jail time. When California leaders politely expelled the research team, they made it clear that investigation and debate were in order. Such internal, collective processes of reflection—and, as a consequence, adaptation of their *usos y costumbres* system—constitute the principle use of the backstage in California. Thus, the social backstage appears to be the mechanism for evolution of local institutions, in that it provides space for discussion, negotiation, and revision without disrupting social codes or public displays of cooperation. *Usos y costumbres* are accumulated local knowledge, so their evolution is also a process of social learning. This process probably involves combining knowledge from local and outside sources and suggests a dynamism often missing in anthropological accounts of traditional governance systems in Mexico [32, 33].

3.7. Governance frameworks: local *versus* national

Mexico's dense history of land-based social relations provides a vantage point for understanding tensions between local communities and nature reserve governance structures. Communal, territory-based agriculture and land governance characterized pre-Hispanic social systems throughout the Americas. Colonial land arrangements were designed primarily to dispossess indigenous peasants from their land, in order to harness their labor in mining and timber industries. At the same time, a majority of indigenous rural communities in southern Mexico remained intact while subject to taxes, in an arrangement called *encomienda* or *cargo*.[9] After the independence of Mexico, large private estates (known as *latifundios* in Latin America but popularly called *fincas* in Chiapas) began to dominate the more fertile lands and incorporate dispossessed farmers as serfs. Agrarian concentration became so pronounced that by the beginning of the twentieth century, peasant discontent had reached revolutionary levels, and uprisings engulfed the nation.

Written in the heat of the Mexican Revolution, the Constitution of 1917, different forms of peasant land tenure were explicitly created: (a) social, (b) collective, and (c) small private property. Particularly, collective land tenure was relied in the *ejido*, a form of inalienable local land sovereignty. This was to be the basis for the top-down agrarian reforms that reorganized and reallocated over half the nation's agricultural lands in the 1930s [19]. The growth of the *ejido* in Mexico was the first and main widespread and institutional credit of the land's social functioning [34]. The Constitution of 1917 entitled rural communities to a degree of self-regulation of land, water, forest, and wildlife use, as described in Article 27 of the same document [35]. This clause recognized rural communities as rightful social entities in regard to the use, management, and regulation of natural resources within the territory that each village encompasses [36]. As a political unit, *ejidos* were both the basis for self-rule by peasant communities and clients of the Mexican ruling political party [37].

In the 1980s and 1990s, the Mexican government's previous strategy of rural development was dramatically reversed as the country's leaders embraced the "free market" model. By adopting such a model, they ended a period of decades of guaranteed prices for staple crops, officially discontinued agrarian reform, and shifted subsidies from peasant agriculture extension services to export-based commercial agriculture. While this "retreat from the countryside" was felt across Mexico, it was in fact an asymmetrical policy shift, as large subsidies for new specialized farms appeared in the northern states, and new programs for cash transfer poverty mitigation and natural resource conservation were introduced almost simultaneously in southern Mexico [38]. As a general trend, *ejido* dwellers became increasingly dependent on various

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[9] *Encomienda* and *cargo* are the Spanish words for "assignment," "task," or "duty."

kinds of poverty mitigation payments, which replaced agricultural production as the primary source of income in rural Mexico [39].

In areas where traditional political systems remained in place throughout the existence of the Mexican nation, communities were given the option to maintain or adopt local governance systems based upon *usos y costumbres*. These local codes and laws based on customs were thus officially recognized by the national state and municipal legal systems [40]. One of the purposes of customary laws—as the *usos y costumbres*—is not only to regulate the village's common use of natural resources like forests, soil and water based on local values, justice, and usage patterns but also to sanction by tradition when necessary improper social acts and faults. According to [9, 32, 33], it can be considered not only as a unifying mechanism for people and organize their expressions of collectivity throughout the use of natural resources but also as their political life and decision-making processes.

Nevertheless, Mexico's jurisprudential system consists of federal laws applicable at every lower administrative level: states, municipalities, and small communities (**Figure 3**). The laws of the top-down system are based on the *individual form* of proper behavior to ensure social order, as considered by protagonist elements of Mexican society. On the contrary, *usos y costumbres* are based on *collective practice* of daily life in California. Hence, many environmental and rural policies run contrary to local strategies of resource use, as validated by local governance systems and practiced in thousands of rural communities [41]. The failure to develop national policy that corresponds with local perceptions of risks and environmental stewardship is a result of contradictory visions on the Mexican countryside. As a consequence, environmental policies such as those with regard to nature reserves are a source of conflict in places where reserve creation is perceived as a state-led enclosed area, meant to exclude human activities, thereby excluding people from their means of survival [42].

National policy over the last couple of decades has increasingly put land and natural resources into inflexible categories of being either available to the market or not available to anyone [43, 44]. When federal environmental agencies applied punitive measures to California as a whole, the *ejido* remained unified and sharpened its collective distrust of the federal legal system. Punishment to individual members, such as the young men who served jail sentences, had the effect of dividing California. This could be due to the federal legal system's a priori distinction between "good" and "bad" practices, which threatens the California's understanding of its own relationship with common resources. Village self-governance, a central aspect of the postrevolutionary social order, has never been fully integrated into conservation strategies [26].

4. Additional discussion

The tension created by the conflict over fire reflects larger debates over forest fires, biodiversity conservation, and agricultural development in the tropics. Conservation theory has frequently dichotomized land use into two divergent models with high trade-offs between them: conservation for biodiversity and agriculture for development. During the last two decades, neoliberal

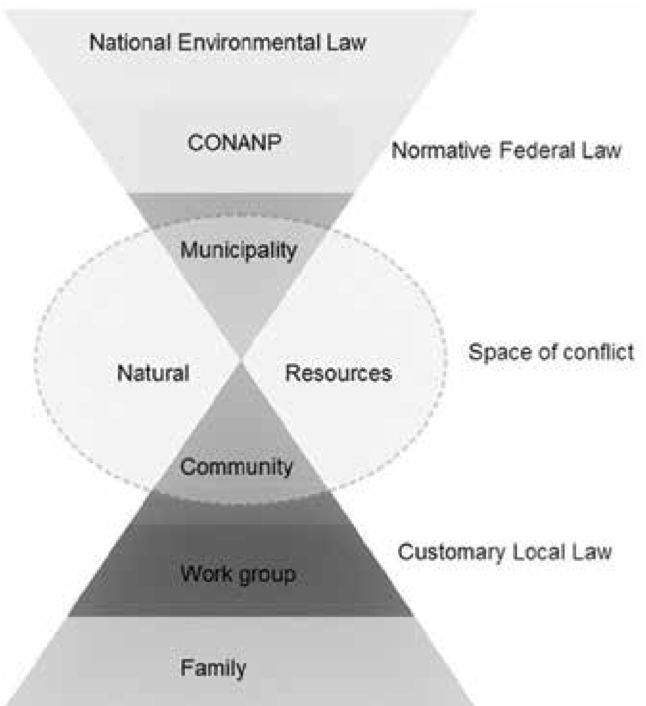

Figure 3. Ruling frameworks for natural resource usage and space of conflict in California (Chiapas, Mexico).

theory has achieved an integration of conservation and development discourses, in forest transition theory [45, 46].

Proponents of forest transition theory suggest that capitalist development in several former colonies has led to increased forest cover, as rural out-migration and increasingly productive industrial agriculture have reduced pressure on agrarian frontiers. Following this logic, the best way for Mexican conservation actors to transition the country from net deforestation to net reforestation would be to implement a twofold strategy: agricultural intensification and a decrease in the agricultural use of forested lands [47]. However, there is a body of ecological theory that challenges forest transition theory and explores the need for larger, landscape-scale conservation strategies that incorporate debates on forest and agricultural models.

Parallel to this theoretical development, many empirical studies have shown a wide array of agroecosystems with biodiversity comparable to natural ecosystems. The agricultural matrix, or cultural-spatial context of nature reserves with vast forested areas, is the key to population survival in this conservation perspective. Therefore, sustainable forest management and smallholder agriculture in the tropics, focused on subsistence and often involving minimum transformation of natural ecosystems, can play a key role in providing biological migration services to the patches of forest that it surrounds.

In ecological terms, the implications of forest fires *versus* landscape matrix debate are essentially a question of whether maintaining large undisturbed habitat patches (such as nature reserves) is more or less important to biodiversity conservation than maintaining high-quality land use between smaller patches of undisturbed habitat. However, both possible answers correspond to two distinct visions of development. Mexico has been an exemplary case of transition to a free market economy, and although rural out-migration has been dramatic, deforestation continues to be the trend [20]. The potential of peasant farmers' *milpa* and *acahual* to serve as migratory corridors and temporary habitat for diverse species has not yet been studied in the Sepultura Biosphere Reserve, neither by government biologists nor external researchers.

5. Concluding remarks

The federal governance system is characterized for its top-down approach, therewith imposing a framework of normative laws that are often badly tuned to local situations [48]. While federally created environmental laws are designed to protect against misuse of vulnerable natural resources, or the use of fire, they are often a source of conflict at the local level [49]. The intimidating character of federal laws, the routines imposed by the *usos y costumbres*, and the lack of local productive opportunities and options have put natural resources at risk and created social tensions, especially by the use of fire in forested areas. It is not surprising, therefore, to find an apparent rise in the illegal use of commons and the breaking of environmental laws in California.

In the relationship between normative and actual behavior, the point of tension became the two frameworks for local practice. The contradictions between the federal laws and the *usos y costumbres* have led to constant misunderstanding of settlers' intentions by municipal and especially federal agencies, as well as the sense of betrayal and abandonment that inhabitants felt. While these relationships have impacts upon the natural resource use and village cohesion, solutions will not be found in technological packages or training, especially those that emphasize the use of fires in forested areas at the level of the individual producer. The traditional crops and cultural practices of California's agriculture form an underlying collective logic that pervades local identity even beyond the cultural use of fire.

Village involvement in biodiversity conservation would require that institutions become capable of learning from peasant traditions rather than only approve or restrict them. Given the trends associated with global climate change in the Sepultura Biosphere Reserve, fire use may be becoming more dangerous and as such could require additional capacity building. However, at a political level, these lessons in coexistence of the two governance systems have yet to become operational in the Sepultura Biosphere Reserves of Mexico. The continued dichotomization of agriculture and conservation obscures sincere efforts of sustainable development, leading to the creation of misguided conservation policy that alienates peasant communities. This can especially have counterproductive effects, as the rural communities are the crucial ally in society's efforts to defend and preserve nature.

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Archetypes of Wildfire Arsonists: An Approach by Using Bayesian Networks

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Abstract

Wildfires are a phenomenon of great importance because of their environmental and economic consequences, as well as the human losses they cause. The rate of resolution of arson-caused wildfires is extremely low when compared to other criminal activities. This fact highlights the importance of developing methodologies to assist investigators in the criminal profiling. For that we propose the use of Bayesian networks (BNs), which are a methodology belonging to the field of machine learning. BNs are probabilistic models that have only recently been applied to criminal profiling.We learn a BN model from real data of solved arson-caused wildfires in Spain, and after validation we use it to construct archetypes of the forest fires/arsonists with the aim of better understanding of this phenomenon and help in the task of identification of the culprits. We characterize five different archetypes around author motivation from a quantitative and objective point of view, which are in correspondence with the modes of operation in criminal activities of Shye.

Keywords: provoked wildfire, arsonist, archetype, profiling, Bayesian networks

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO) survey [1], *"[…] every year, wildfires destroy millions of hectares of forests, woodlands and other vegetation, causing the loss of many human and animal lives and immense economic damage, both in terms of resources destroyed and the costs of suppression. There are also impacts on society and the environment […]"*. Mediterranean countries are especially sensitive to this phenomenon due to the characteristics of their vegetation, land use, and climate. On the average, 50, 000 fires burn 400, 000 hectares every year in these regions (San-Miguel-Ayanz, Moreno and Camia [2]), and the situation is worsening due to the effect of climate change (Turco, Llasat, von Hardenberg and

Provenzale [3]). According to the Ministry of Agriculture and Fishery, Food and Environment of Spain [4], in period 2006–2015, a yearly average of 13, 126 forest fires burned 133, 060 hectares. As a consequence, this phenomenon is one of the major environmental problems in Spain.

In this work, we are interested in the arson-caused wildfire, understood as "the uncontrolled fire on forest land caused by humans that spreads quickly out control over woodland or brush, affecting vegetation that was not destined to burn" (this definition does not include the burning of stubble, grass, or scrub for the removal of forest residues, unless they are carried out where they are prohibited).

From a quantitative point of view, wildfires have been studied mainly from the point of view of risk assessment. Just to mention some studies, Thompson, Scott Helmbrechet and Calvin [5] present an integrated and systematic risk assessment framework to better manage wildfires and to mitigate losses to highly valued resources and assets, with application to an area in Montana, United States, while Penman, Bradstock and Price [6] study the patterns of wildfires in south-eastern Australia in relation to risk of ignition, and Adab, Kanniah and Solaimani [7] consider different fire risk indices in northeastern Iran. In the criminological context, Cozens and Christensen [8] analyze how environmental criminology can help to prevent arson-caused wildfires in Australia, where this phenomenon also represents a serious problem.

Although arson is one potential cause of many fires, yet the rate of clarification of arson-caused wildfires is extremely low when compared to other criminal activities. According to the interim report of the Ministry of Agriculture and Fishery, Food and Environment of Spain [9], 11, 928 wildfires were committed in 2015 in Spain, of which 429 offenders have been identified, representing a resolution rate of 6–6.5% since the estimated percentage of wildfires in Spain that were deemed arson in 2015 ranges from 55 to 60%. This fact highlights the difficulty in identifying the authors of provoked forest fires. Therefore, any help in developing methodologies that can aid investigators to better understand motivation of arsonists in order to solve and, if possible, to prevent these crimes, is welcome. In this sense, our main aim is to find predictive relationships between different typologies of forest fire and the characteristics of the perpetrators, by constructing archetypes taking into account both author features (behavioral, criminological, socio-demographic, and of personality) and evidences obtained from the fire, in order to assist people with responsibilities in the judicial investigation, increasing the rate of clarification of crimes and misdemeanors. Our work is framed into a project led by the Prosecution Office of Environment and Urbanism of Spain, which is carried out by a team in which members of the Crime Behavior Analysis Section of the Technical Unit of the Judicial Police of the Civil Guard participate.

Apart from some few descriptive studies as Soeiro and Guerra [10], to our knowledge the only quantitative approaches to this question stem from the works of Sotoca, González, Fernández, Kessel, Montesinos and Ruz [11] and Delgado, González, Sotoca and Tibau [12]. More specifically, the approach followed in Sotoca et al. [11] consists in the application of different techniques of statistical multivariate analysis (mainly, cluster analysis) to criminal profiling, based on the premise that the crime scene contains clues that if properly collected and interpreted, could say something about the person who set the fire. Otherwise, in Delgado et al. [12], the methodology of Bayesian networks (from now on, BNs) was applied for the first time to profiling of wildfire arsonists. BNs had only recently been applied to criminal profiling (see, for instance, Baumgartner, Ferrari and Palermo [13] and Baumgartner, Ferrari and Salfati [14]) and as far as we know, never before for profiling of any kind of arsonist.

The unpredictability of human behavior adds a component of randomness to all our activities, the criminal among them. BNs are an increasingly popular methodology in the field of machine learning for modeling uncertain in complex domains, and in the opinion of many Artificial Intelligence researchers, the most significant contribution in this area in the last years (Korb and Nicholson [15]). Indeed, BNs are of the most effective machine learning techniques and fall in the field of supervised learning, along with other techniques such as support vector machines, kernels, or neural networks.

BNs were introduced in the 1920s as a probabilistic tool to model the relationships among different variables. Usefulness of this methodology has been shown in many decision-making procedures and in different areas. In particular, it has been used with a great success in risk analysis in ecology (Ticehurst, Newham, Rissik, Letcher and Jakeman [16]), economy (Adusei-Poku [17]), emerging diseases (Walshe and Burgman [18]), environmental sciences (Borsuk, Stow and Reckhow [19] and Pollino, Woodberry, Nicholson, Korb and Hart [20]), medecine (Spiegelhalter [21], and Cruz-Ramrez, Acosta-Mesa, Carrillo-Calvet, Alonso Nava-Fernández and Barrientos-Martnez [22]), or nuclear waste accidents (Lee and Lee [23]). And with respect to criminology, for example, BNs have been introduced as a novel methodology for assessing the risk of recidivism of sex offenders in Delgado and Tibau [24].

Regarding wildfires, Papakosta and Straub [25] study a wildfire building damage consequences assessment system constructed from a BN, and applies it to spatial datasets from the Mediterranean island of Cyprus. Dlamini develops a BN model in [26] from satellite and geographic information systems (GIS), with variables of biotic, abiotic, and human kind, in order to determine factors that influence wildfire activity in Swaziland (see also Dlamini [27]). As mentioned above, Delgado et al. [12] is the only previous study on the use of BN for profiling of the author of a forest fire. The authors also implement this methodology for criminal profiling in an Internet computer application to be used by the Prosecution Office of Environment and Urbanism.[1]

In this chapter, we set two objectives: in the first place, we intend to introduce BN and explain their application to the study of profiles of forest arsonists. Secondly, we go beyond Delgado et al. [12] into the use of this methodology for a better understanding of wildfire arsonists motivation, constructing archetypes which will help to identify the culprits. For that, we learn a BN model from the updated available data provided by the Spanish government, and use it to study motivation and for the construction of archetypes from the characteristics of an arson-caused wildfire and offender features. Roughly speaking, we construct the most probable BN given the observed cases (learning procedure), and this model provides information on the relationships between the considered variables, which are both fire features and author

[1]Delgado R, Tibau XA. "PerfilNet.Pyros: Expert System based on Bayesian networks for the prediction of criminal profiles in forest fires". Register on June 10, 2016 of authorship at the "Benelux Office for Intellectual Property" (BOIP), with reference number i-depot number: 088029.

characteristics, allowing us to carry out predictions about some of them (query variables) from other (evidences).

The organization of the chapter is as follows. In Section 2, we introduce the research methods we use, starting with an introduction to the theoretical framework that supports profiling and archetypes, a description of the dataset on which we rely to construct our BN model, and a description of the model itself. Complementary and more technical information of the latter topic can be found in Appendix A. In Section 3, we apply the previously constructed BN to develop archetypes for forest fires/arsonists based on motivation. The chapter finishes with a conclusion section.

2. Research methods

2.1. Theoretical framework

As the comprehensive literature review, Dowden, Bennell and Bloomfield [28] showed that most criminal profiling publications do not provide any clear theoretical framework on the rationale of the profiling process, and only a few articles reported the use of statistical techniques (most of them multivariate). For this reason, some authors criticize the use of profiling and call it "pseudoscientific practice", as Snook, Cullen, Bennell, Taylor and Gendreau [29], while police officers see it with some skepticism (Snook, Haines, Taylor and Bennell [30]) and the mental health professionals of the forensic environment also show their doubts about it (Torres, Boccaccini and Miller [31]).

In the United Kingdom, however, scientific literature that overcome previous criticisms has been available for more than 20 years, and has led to a new methodological approach to profiling known as "Behavioral Investigative Advice". This approach takes into account evidence-based knowledge to aid decision-making by the police investigator, and includes many other tasks such as crime scene assessment, case-link analysis, suspect prioritization matrices, counseling in the police interview, etc. (see Alison and Rainbow [32]). The origin of this new perspective began with the studies of Canter, in which multidimensional scaling was applied to datasets of solved crimes in order to obtain clusters or profiles, in the first place of the crimes themselves, and later of the authors, to finally calculate the statistical correlation with each other. In this way, depending on how the crime was committed, it could be assigned to a profile, which would automatically report the characteristics of the author who most often commits this type of crime. In addition, Canter offered a theoretical model that helped interpret the results: *Shye's model of action system* (Shye [33]). This methodology was applied to the elaboration of profiles of arsonists (Canter and Fritzon [34]; Fritzon, Canter and Wilton [35]) and was continued in other works, such as Fritzon [36], in which it was applied to study the relationship between the distance traveled by the arsonists and their motivation; Kocsis and Cooksey [37], which is focused on serial arsonists; and Wachi, Watanabe, Yokota, Suzuki, Hoshino, Sato and Fujita [38], in which the incendiary women in Japan are studied.

However, in spite of so many antecedents, all these authors address the incendiary phenomenon in general, not the forest fire in particular. The only work specifically forestry previous to

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the studies carried out in Spain is the aforementioned Viegas and Soeiro [39] where, taking into account the model of action system and using multiple correspondence analysis, four profiles of forest arsonist in Portugal were proposed, denominated: “expressive with clinical history”, “expressive with attraction by the fire”, “vengeful instrumental”, and “instrumental to obtain profit”. Each of these profiles involves a series of identifying characteristics of its authors and a distinctive way of committing forest fires, depending on whether the main motivation was revenge, psychiatric problems, pathological attraction for fire, or obtaining an economic profit.

The work carried out in Spain Sotoca et al. [11] is inspired by the aforementioned Portuguese study and explores other data analysis methodologies, specifically techniques of multivariate statistical analysis, to establish an a priori classification of forest fires according to their cause or motivation, resulting in the following basic archetypes: “negligence”, which opposes “intentional”, being mutually exclusive. Intentional fires were grouped into four subtypes, also mutually exclusive: “profit’, “revenge”, “impulsive”, and “inadequate traditional practice”. This classification is consistent with the four modes of operation of the theoretical framework of criminal activities of Shye, and the correspondence among them is shown in **Table 1**.

As in Delgado et al. [12], in this chapter, we consider a slight modification of the archetypes constructed in Sotoca et al. [11]: we stack “negligence” and “inadequate traditional practice” into “negligence”, since in both cases the fire occurs as a consequence of a recklessness, but distinguishing between “slight negligence” and “gross negligence”, depending on whether the perpetrator remains on site and helps extinguishing services, in the first case, or not. The rest of archetypes have not been modified. Then, the list of updated archetypes and their correspondence with modes of operation is given in **Table 2**. This is in line with the proposal of the five

Former forest fire classification	Mode of operation
Negligence	Adaptive
Inadequate traditional practice	Adaptive
Impulsive	Integrative
Profit	Expressive
Revenge	Conservative

Table 1. Equivalence between former classification given in Sotoca et al. [11] and mode of operation in Shye [33].

Present forest fire classification	%	Mode of operation
Slight negligence	47.64	Adaptive
Gross negligence	31.30	Adaptive
Impulsive	10.05	Integrative
Profit	7.59	Expressive
Revenge	3.42	Conservative
	100.00	

Table 2. Equivalence between present classification and mode of operation in Shye [33].

main profiles of forest fire from an "operational" character, each one with its own author profile, found in previous years and confirmed by the most recent statistical analysis carried out by the team working in this project. It is important to note that "impulsive", "profit", and mainly "revenge" are uncommon compared to the rest. Motivation has been recorded in $1,463$ of the $1,597$ solved cases in our database, and in **Table 2** we show the percentages of each motivation type.

In Delgado et al. [12] and in this chapter, the use of BN is proposed as an alternative to the analysis used in Sotoca et al. [11], since BNs allow to know not only if the way of committing a forest fire is associated with some characteristic of the author, but to quantify this association, which gives the fire investigator far more accurate information. BNs are a machine learning methodology of self-learning from the data that can be used with success in the social sciences, where efforts to find scientific laws on human behavior often fail to establish a conceptual framework to guide empirical observation and the method of analysis corresponding to that framework.

As mentioned in Section 1, our aim is to present BN as a methodology to improve understanding of the different types of motivations from a quantitative and objective point of view, helping in the construction of archetypes.

2.2. The dataset

Statistical information on the phenomenon of forest fires has been collected in Spain since 1968, generating one of the most complete databases in Europe and been pioneer worldwide. This information is currently managed by the General Directorate of Natural Environment and Forestry Policy of the Ministry of Agriculture and Fishery, Food and Environment of Spain. However, our database consists of policing clarified arson-caused wildfires (for which the alleged offenders have been identified), has been feeding since 2008 by the Secretary of State for Security throughout the entire Spanish territory, under the leadership of the Prosecution Office of Environment and Urbanism of the Spanish state, and contains information obtained from a specific questionnaire concerning authors that have been arrested or imputed.

As mentioned above, adding certain and supposed causes it seems that the percentage of wildfires in Spain that were intentional ranges from 55 to 60% (close to other countries like Australia, Cozens and Christensen [8]), while it was only possible to identify 6–6.5% of the arsonists. Given these numbers, it could be said that the intentional forest fire is a criminal activity with very low rate of clarification, which explains the interest of the involved authorities and the society in general, in increasing the rate of clarification.

This subset conforms our dataset, which contains 1597 solved cases. According to the expert's knowledge, $n = 25$ variables have been chosen of the total set of 32 initial variables, because of their usefulness and predictive relevance. The choice is the result of a balance between the benefits of having a high number of variables (more realistic model with higher accuracy) and the drawbacks arising from the corresponding increasing complexity (implying the need for more data to learn the model properly). The chosen variables refer to crime ($C_1, \ldots, C_{10}$) and to the arsonist ($A_1, \ldots, A_{15}$), and are described in **Table 3**, where their possible outcomes are also

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Variables	**Outcomes**
C_1 = season	Spring/winter/summer/autumn
C_2 = risk level	High/medium/low
C_3 = start time	Morning/afternoon/evening
C_4 = starting point	Pathway/road/houses/crops/interior/forest track/others
C_5 = main use of burned surface	Agricultural/forestry/livestock/interface/recreational
C_6 = number of seats	One/more
C_7 = related offense	Yes/no
C_8 = pattern	Yes/no
C_9 = traces	Yes/no
C_{10} = who denounces	Guard/particular/vigilance
A_1 = age	$\leq$34/35 − 45/46 − 60/> 60
A_2 = way of living	Parents/in couple/single/others
A_3 = kind of job	Handwork/qualified
A_4 = employment status	Employee/unemployed/sporadic/retired
A_5 = educational level	Illiterate/elementary/middle/upper
A_6 = income level	High/medium/low/without incomes
A_7 = sociability	Yes/no
A_8 = prior criminal record	Yes/no
A_9 = history of substance abuse	Yes/no
A_{10} = history of psychological problems	Yes/no
A_{11} = stays in the scene	No/remains there/remains and gives aid
A_{12} = distance home-scene	Short/medium/long/very long
A_{13} = displacement means	On foot/ by car/all terrain/others
A_{14} = residence type	Village/house/city/town
A_{15} = motivation	Slight negligence/gross negligence/impulsive/profit/revenge

Table 3. Outcomes of the variables in the dataset.

shown. The incendiary variables $A_1, \ldots, A_{15}$ correspond to aspects that are easily observable and have some police relevance, which is very convenient since they are intended to guide the police activity to clarify the crime. We use exclusively categorical variables, by discretizing the (few) continuous variables in the original database. Approximately 78% of cases have missing values in at least one of the variables, mostly variable authors, which are the ones that have the most missing cases. Because it is a very high percentage, instead of omitting cases containing at least one missing value, which is a standard practice, we replace missing values by a new value different from the rest of the outcomes (a "blank", in our case), treating missing values as a unique value and not mapping them into any other. In this way we do not lose information. Once obtained the predictions for each query variable, the "blank" value is eliminated from prediction and its probability is proportionally divided among the rest of its outcomes.

2.3. Constructing the BN

BNs are graphical structures for representing the probabilistic relationships among the variables describing a random phenomenon, such as in our setting provoked forest fires, and for performing probabilistic inference with them. Given a set of random variables $V = \{X_1, \dots, X_n\}$, a BN is a model that represents the joint probability distribution P over those variables. In our case, $V = \{C_1, \dots, C_{10}, A_1, \dots, A_{15}\}$ and $n = 25$. The graphical representation of the BN consists of a *directed acyclic graph* (DAG), whose n nodes represent the random variables (from now on, we identify a node with the variable that represents). The directed arcs among the nodes represent conditional dependencies between variables. **Figure 1** shows the DAG corresponding to the BN that has been constructed (learned from data).

We can use the BN to help in characterizing a provoked wildfire in terms of the relationships between different variables. These relationships are expressed in a very simple way in the BN, through the absence/presence of directed arcs in its DAG, taking into account the *Markov condition*, which stays the following: *"knowing the values that its* ***parents*** *take, which are the nodes sending a directed arc to it in the DAG, any variable is independent of any other which is not a parent nor a* ***descendant*** *of it (a "descendant" of a node is any other node to which is possible to arrive from it*

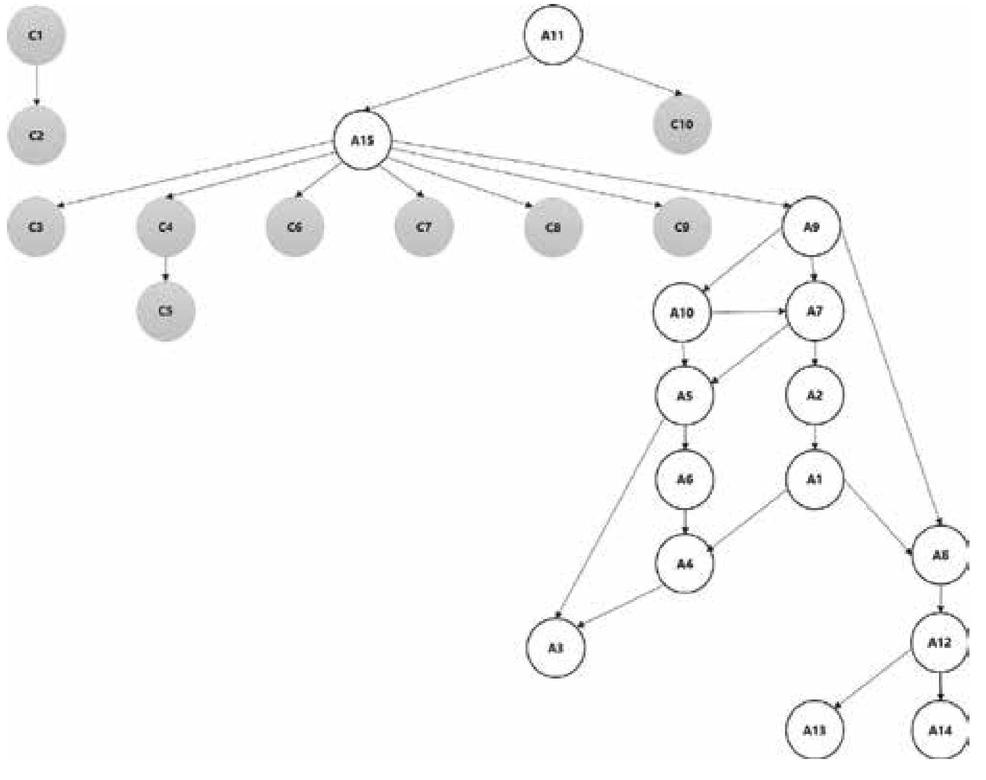

Figure 1. Learned structure (DAG) of the BN from the dataset.

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by following a path linking directed arcs)". For example, observing **Figure 1** we can see that known the value of variable A_{15}, C_4 is independent of any other variable except C_5, since C_5 is its unique descendant. Just to mention another example, if we know the outcome of variable A_8, then A_{12} is independent of the rest of variables except A_{13} and A_{14}.

Once learned the BN model from the dataset, both the structure (DAG) and the *parameters* (the probability distribution of each variable conditioned to its parents), we can use it to compute any *a posteriori* probability we are interested in: we can consider an evidence concerning some variables of the model and use the BN to update the (*a priori*) probability distribution of any of the rest of variables, knowing the evidence. More specifically, from an evidence of the form $E = \{X_{i_1} = x_{i_1}, \dots, X_{i_\ell} = x_{i_\ell}\}$, where $\{X_{i_1}, \dots, X_{i_\ell}\} \subset V$ are the *evidence* variables, we could be interested in computing the *a posteriori* (conditioned) probability $P\left(X_{j_1} = x_{j_1}, \dots, X_{j_s} = x_{j_s}/E\right)$ with $\left\{X_{j_1}, \dots, X_{j_s}\right\} \subset V \backslash \{X_{i_1}, \dots, X_{i_\ell}\}$ the set of *query* variables. This probability is the update when we noticed and additional piece of knowledge, of the corresponding *a priori* probability, which would be the same but without conditioning with respect evidence E. Given an evidence E, the prediction of the query variable X is chosen to be the instantiation of X that maximizes the *a posteriori* probability. In a more formal way, if $x_1, \dots, x_r$ are the possible instantiations of X, then $x^* = arg\,max_{k=1,\dots,r} P(X = x_k/E)$ is the prediction for X knowing evidence E, and $P(X = x^*/E)$ is said to be the *confidence level (CL)* of the prediction. We will apply this procedure to our setting in the following way: given an evidence in terms of the crime (evidence) variables for a given provoked forest fire, we will predict the value of the query arsonist features (query variables), which form the predicted profile of the arsonist. Interested readers can find technical details about the construction and validation of the BN in Appendix A.

All calculations, as well as the process of model construction, validation, and inference, have been carried out with **R**, which is "GNU S", a freely available language and environment for statistical computing and graphics, which provides a wide variety of statistical and graphical techniques. It can be obtained from the CRAN site https://cran.r-project.org/. Different packages of R has been adopted:

- **bnlearn**: Bayesian Network Structure Learning, Parameter Learning and Inference, by Marco Scutari and Robert Ness, http://www.bnlearn.com/

  We use this package for Bayesian network structure learning and parameter learning, using the score-based Hill-Climbing structure learning algorithm and maximum likelihood parameter estimation, respectively.

- **gRain**: Graphical Independence Networks, by Søren Højsgaard, http://people.math.aau.dk/ sorenh/software/

  We use this package for making inference by probability propagation with the BN learned by using the bnlearn package.

- **sna:** Tools for Social Network Analysis, by Carter T. Butts, http://www.statnet.org.

  From this package, we use some social network analysis measures in Section 3.1.

3. Archetypes

In this section we use the BN model learned from the dataset and described in Section 2, to construct forest fire archetypes related to arsonist motivation.

First of all, note that author variables A_8 ="prior criminal record", A_9 ="history of substance abuse", and A_{10} ="history of psychological problems" are operative variables of practical use so that the investigators can identify the author of a provoked fire. Fortunately, these variables have a good accuracy in prediction with the BN model, higher than 80%. See **Table 4**, where accuracies, both individual for the prediction of each author variable (IPA), as well as overall (OPA), are consigned.

3.1. Why motivation?

We use motivation (A_{15}) as a cornerstone from which to construct the archetypes by two reasons: (1) from a viewpoint of the theoretical framework, motivation plays a key role in criminological investigations (see Collin [40]), and as explained in Section 2.1, in order to meet Shye's classification for criminal activities, motivation should be taken as classification criterion, and (2) A_{15} is the author variable with the most central role and explanatory capacity of fire characteristics in the model.

Indeed, 8 of the 10 nodes representing crime variables are directly related to it. More concretely, 7 of them are descendants (from C_3 to C_9, being all of them "sons" of A_{15}, except C_5,

Author variable	**IPA (%)**
A_1 = age	33.13
A_2 = way of living	60.40
A_3 = kind of job	72.28
A_4 = employment status	44.62
A_5 = educational level	46.24
A_6 = income level	46.96
A_7 = sociability	97.02
A_8 = prior criminal record	80.19
A_9 = history of substance abuse	90.58
A_{10} = history of psychological problems	89.56
A_{11} = stays in the scene	60.49
A_{12} = distance home-scene	45.13
A_{13} = displacement means	34.38
A_{14} = residence type	47.12
A_{15} = motivation	56.36
Total OPA (%).	58.12

Table 4. Individual predictive accuracy (IPA) and overall predictive accuracy (OPA).

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which is a "grandson"), and one, C_{10}, is a "brother", that is, it is a son of the father of A_{15}, which is A_{11} (see **Figure 1**). The main role of A_{15} in the model can be quantified by using centrality and/or betweenness measures borrowed from the Network Analysis area. In Graph Theory and Network Analysis, indicators of centrality identify the most important nodes within a graph. Here, "importance" is conceived as involvement in the cohesiveness of the network. Applications of centrality include identifying the most influential person(s) in a social network, key infrastructure nodes in the Internet or urban networks, and super-spreaders of a disease. Concretely, for each author variable we computed two measures, which are shown in **Table 5**, both normalized in order to sum up 100:

a. *Freeman's degree of centrality* (Freeman [41]), which counts paths which pass through each node, that is, directed arcs which arrive at or depart from it. **Table 5** points out A_{15} as the author variable with the most central role, doubling the value of the following in the ranking.

b. *Borgatti and Everett's betweenness measure* (Borgatti and Everett [42]). Betweenness quantifies the number of times a node acts as a "bridge" along the shortest path between two other nodes (which we will call "geodesic" from now on). Nodes that have a high probability to occur on a randomly chosen geodesic between two randomly chosen nodes, have a high betweenness. Borgatti and Everett's betweenness is a modification of a basic

Author Variables	Freeman's Centrality (%)	Borgatti and Everett's Betweenness (%)
A_1 = age	6.67	9.36
A_2 = way of living	4.44	8.17
A_3 = kind of job	4.44	0.00
A_4 = employment status	6.67	2.90
A_5 = educational level	8.88	9.74
A_6 = income level	4.44	3.07
A_7 = sociability	8.88	11.36
A_8 = prior criminal record	6.67	12.68
A_9 = history of substance abuse	8.88	14.94
A_{10} = history of psychological problems	6.67	3.33
A_{11} = stays in the scene	4.44	0.00
A_{12} = distance home-scene	6.67	9.72
A_{13} = displacement means	2.23	0.00
A_{14} = residence type	2.23	0.00
A_{15} = motive	17.77	14.68
	100.00	100.00

Table 5. (Normalized) Freeman's degree of centrality and Borgatti and Everett's betweenness measure of the author variables.

standard betweenness measure, which was defined for a node v as $\sum_{i,j\,\text{nodes}} \frac{g_{ivj}}{g_{ij}}$ (with the convention $0/0 = 0$), where g_{ij} is the number of geodesics from i to j in the graph, and g_{ivj} is the number of geodesics in the subset of those that pass through v. The modification proposed by Borgatti and Everett is as follows:

$$\sum_{i,j\,\text{nodes}} \frac{1}{d_{ij}} \frac{g_{ivj}}{g_{ij}} \tag{1}$$

where d_{ij} is the geodesic distance from i to j (that is, the number of directed arcs that compose any geodesic from i to j). Conceptually, using the basic standard betweenness measure, high-betweenness nodes lie on a large number of non-redundant geodesics between other nodes; they can thus be thought of as "bridges". Borgatti and Everett's betweenness adjusts the basic standard by down-weighting long geodesics, and attending to it we see in **Table 5** that A_{15} is the second most important after, but very close, to A_9.

3.2. Constructing archetypes

The explained above justifies the decision to base our archetypes of provoked forest fires on A_{15}. Therefore, we construct some archetypes around motivation, and comparing them with that in Sotoca et al. [11], we see they are consistent. To carry this out, we predict query variables $C_1, \ldots, C_{10}, A_1, \ldots, A_{14}$ by introducing as evidence the different possible outcomes of variable A_{15}. Some of the crime variables, and most of the author variables are insensitive, that is, they coincide for the consigned five possible criminal motivations, and for any of them always have the same predicted values, which are collected in **Table 6**.

In case of C_1 and C_2, it is not surprising since, as can be seen in **Figure 1**, they are not related neither with A_{15} nor with any other variable in our model. Coinciding with common sense, for each of these two variables the most probable value is chosen, independently of the evidence variable A_{15}.

Explanation for each of the variables appearing in **Table 6** that are sons of A_{15}, which are C_6, C_7, and $C9$, is straightforward: we just have to have a look at its conditional probability table (CPT so on), whose values are parameters of the BN model that have been learned from data when constructing it, and observe that conditioned to the different outcomes of A_{15}, the most probable value of any of them does not vary. Simply to illustrate, **Table 7** is the conditional probability table of variable C_6 conditioned to A_{15}. The maximum probability corresponds to the same row when we vary from one column to another, that is, conditioned to any of the possible outcome of A_{15} the prediction of our model for C_6 is always "one".

For the rest of variables in **Table 6**, intuition is no longer reliable since their relation with A_{15} is modeled through a chain of oriented arcs (a path). We can say that, in general, the longer the path linking them, the lesser the mutual influence is between two nodes, which would explain the presence of the author variables in **Table 6**.

Variables not appearing in **Table 6** take different values according to motivation, as **Table 8** shows, and they are those from which we will describe our archetypes. Of the crime variables,

Variable	Predicted value
C_1 = season	Spring
C_2 = risk level	High
C_6 = number of seats	One
C_7 = related offense	No
C_9 = traces	No
C_{10} = who denounces	Particular
A_1 = age	46 − 60
A_2 = way of living	In couple
A_3 = kind of job	Handwork
A_4 = employment status	Employee
A_5 = educational level	Elementary
A_6 = income level	Medium
A_7 = sociability	Yes
A_8 = prior criminal record	No
A_{10} = history of psychological problems	No
A_{12} = distance home-scene	Medium
A_{14} = residence type	Town

Table 6. Common predicted values for all the five archetypes.

C_6↓ A_{15} →	Slight negligence	Gross negligence	Impulsive	Profit	Revenge
More	0.06	0.10	0.33	0.41	0.37
One	**0.94**	**0.90**	**0.67**	**0.59**	**0.63**
	1.00	1.00	1.00	1.00	1.00

Table 7. Conditional probability table (CPT) of C_6 to A_{15}. For example, if A_{15} were "slight negligence", the estimated probability for C_6 ="one" is 0.94, that is, $P(C_6 = \text{"one"}/A_{15} = \text{"slight negligence"}) = 0.94,$ which is the maximum value of its column, being then "one" the prediction for C_6 conditioned to A_{15} ="slight negligence".

C_3, C_4, and C_8 are sons of A_{15}, while C_5 is a grandson. CPTs of C_3, C_4, and C_8 conditioned to A_{15}, whose values are parameters of the model which are learned from data, give a straightforward prediction for each of these variables, which is the most likely predicted value conditioned to each motivation type. With C_5 and A_{13} we have to be more cautious. It is recommended to the interested readers to delve into this aspect, to consult Appendix B.

3.3. Checking, improving, and reducing archetypes

It seems convenient to check the constructed archetypes given in **Table 8**, and we will carry it out as follows. We could ask if using as evidence the values of the variables in **Table 8** for each of the archetypes, and as query variable motivation, the model will predict the concordant archetype. If so, the archetype would be strengthened and would, in a certain sense, be

	Negligence		Intentional		
Variables↓ Archetypes →	(1) Slight negli.	(2) Gross negli.	(3) Impulsive	(4) Profit	(5) Revenge
C_3 = start time	Afternoon	Afternoon	Afternoon	Afternoon	Evening
C_4 = starting point	Crops	Crops	Pathway	Pathway	Pathway
C_5 = main use surface	Agricultural	Agricultural	Forestry	Forestry*	Forestry
C_8 = pattern	No	No	Yes	Yes	No
A_9 = history subst. Abuse	No	No	No	No	Yes
A_{11} = stays in the scene	Gives aid	No	No	No	No
A_{13} = displacement means	By car	By car	On foot	By car	On foot

*the second most likely outcome, "agricultural", has a very close probability to that of "forestry", as can be seen in **Table 15**, Appendix B.

Table 8. Specific predicted values for each of the five archetypes (extended version).

validated. But it may not happen, because we do not obtain the same probabilities conditioning C_4 by A_{15}, for example, that vice versa. Indeed, to exemplify this fact, we set specific values for these variables, say "pathway" and "impulsive", respectively, and we will see that

$$P\big(C_4 = \text{“pathway”}/A_{15} = \text{“impulsive”}\big) \neq P\big(A_{15} = \text{“impulsive”}/C_4 = \text{“pathway”}\big). \quad (2)$$

The reason appears clearly when using Bayes' Theorem we relate these two probabilities:

$$P\big(A_{15} = \text{“impulsive”}/C_4 = \text{“pathway”}\big) = \frac{P\big(C_4 = \text{“pathway”}/A_{15} = \text{“impulsive”}\big)\,P\big(A_{15} = \text{“impulsive”}\big)}{P\big(C_4 = \text{“pathway”}\big)}, \quad (3)$$

That is, these probabilities are related by means of the multiplicative factor

$$\frac{P\big(A_{15} = \text{“impulsive”}\big)}{P\big(C_4 = \text{“pathway”}\big)} \cong \frac{0.1005}{0.1490} \cong 0.6745 \quad (4)$$

in this way:

$$P\big(A_{15} = \text{“impulsive”}/C_4 = \text{“pathway”}\big) = 0.6745 \times P\big(C_4 = \text{“pathway”}/A_{15} = \text{“impulsive”}\big). \quad (5)$$

Table 9 shows the CPT of A_{15} to the evidences given by the values of variables in **Table 8**. The predicted (most likely) value for A_{15} appears in boldface

Looking at **Table 8**, we note that the only difference between the archetypes **impulsive** and **profit** is given by A_{13}. Will this difference propagate to A_{15}? **Table 9** tells no, since the conditional probability tables of A_{15} for the corresponding evidences match, and we see that **impulsive** is the only archetype given by **Table 8** that has not been confirmed by **Table 9**. Could we modify this archetype in some sense to better adapt to data and result in an improved version? Actually yes.

Archetype	Evidence variables	Value	Conditioned distrib. of A_{15} to evidence
(1)	C_3 = wildfire start time	Afternoon	Profit (0.25%)
	C_4 = starting point	Crops	Gross negligence (0.00%)
	C_5 = main use of surface	Agricultural	**Slight negligence (**99.72%**)**✓
	C_8 = pattern	No	Impulsive (0.03%)
	A_9 = traces	No	Revenge (0.00%)
	A_{11} = stay in the scene	Gives aid	
	A_{13} = displacement means	By car	
(2)	C_3 = wildfire start time	Afternoon	Profit (2.79%)
	C_4 = starting point	Crops	**Gross negligence (**96.75%**)**✓
	C_5 = main use of surface	Agricultural	Slight negligence (0.00%)
	C_8 = pattern	No	Impulsive (0.31%)
	A_9 = traces	No	Revenge (0.15%)
	A_{11} = stay in the scene	No	
	A_{13} = displacement means	By car	
(3)	C_3 = wildfire start time	Afternoon	**Profit (**39.39%**)χ**
	C_4 = starting point	Pathway	Gross negligence (22.02%)
	C_5 = main use of surface	Forestry	Slight negligence (0.00%)
	C_8 = pattern	Yes	Impulsive (32.85%)
	A_9 = traces	No	Revenge (5.74%)
	A_{11} = stay in the scene	No	
	A_{13} = displacement means	On foot	(It should be **Impulsive**)
(4)	C_3 = wildfire start time	Afternoon	**Profit (**39.39%**)**✓
	C_4 = starting point	Pathway	Gross negligence (22.02, %)
	C_5 = main use of surface	Forestry/agricultural	Slight negligence (0.00%)
	C_8 = pattern	Yes	Impulsive (32.85%)
	A_9 = traces	No	Revenge (5.74%)
	A_{11} = stay in the scene	No	
	A_{13} = displacement means	By car	
(5)	C_3 = wildfire start time	Evening	Profit (4.56%)
	C_4 = starting point	Pathway	Gross negligence (5.15, %)
	C_5 = main use of surface	Forestry	Slight negligence (0.00%)
	C_8 = pattern	no	Impulsive (24.52%)
	A_9 = traces	Yes	**Revenge (**65.77%**)**✓
	A_{11} = stay in the scene	No	
	A_{13} = displacement means	On foot	

Table 9. Checking archetypes given in **Table 8**.

Let us go back for a moment to **Table 8**. Given an evidence as, for example, A_{15} ="profit", we predict query variables appearing in the table (and the rest as well) *as if they were independents*. This assumption make the calculations for predictions feasible, since if this assumption were not made, calculations would be so large that they would easily overflow the calculating capacity of a personal computer. But is it realistic? By the Markov condition, given A_{15} known, the independency among variables appearing in **Table 8** can be assumed (approximately in case of A_9 and A_{13}, because although A_{13} is a descendant of A_9, the length of the geodesic that connects them weakens dependency) except in one case: C_4 and C_5. Fortunately, it is feasible to carry on the calculations to obtain the joint probability distribution of C_4 and C_5 conditioned to A_{15}, and making the joint prediction of both (that is, taking the values that maximize this joint distribution), this prediction improves that made separately assuming an independence that is far from certain. For example, conditioned to A_{15} ="impulsive", the combination of values of C_4 and C_5 that maximizes the joint probability distribution is: C_4 ="road" and C_5 ="forestry". By replacing C_4 ="pathway" by C_4 ="road" in archetype (3) of **Table 9**, we obtain the conditioned distribution of A_{15} to the evidence given by the evidence variables in **Table 10**.

For the rest of archetypes, the joint predictions of C_4 and C_5 are exactly the same as the separated ones assuming independency, except for **revenge**. In this case, the joint prediction is C_4 ="forest track" and C_5 ="forestry". If substitute C_4 ="pathway" by C_4 ="forest track" while maintaining C_5 ="forestry" in **Table 9**, archetype (5), the probability of predict **revenge** increases from 65.77 to 76.45%.

Finally, for each archetype we can eliminate some of the variables without a great loss, those that are superfluous in the sense that if we do not include them as part of the evidence, the conditioned probability of A_{15} does not change excessively, maintaining the same prediction (value that maximizes probability). The improved and reduced version of the archetypes are given in **Table 11**. Naturally, the archetypes with the highest confidence level (CL) are those that correspond to both types of negligence, which are the most frequently consigned motivations in the dataset. We summarize the main distinctive features of each archetype:

- **Negligence** is characterized because the starting point of the fire is **crops**, and the main use of the burned surface is **agricultural**. The only difference between **slight** and **gross** negligence is that in the first case arsonist stays at the scene and **gives aid** while in the

Modified archetype	Evidence variables	Value	Conditioned distrib. of A_{15} to evidences
(3)	C_3 = wildfire start time	Afternoon	Profit (25.62%)
	C_4 = starting point	**Road**	Gross negligence (13.22%)
	C_5 = main use of surface	Forestry	Slight negligence (0.00%)
	C_8 = pattern	Yes	**Impulsive (**54.32%**)**✓
	A_9 = traces	No	Revenge (6.84%)
	A_{11} = stay in the scene	No	
	A_{13} = displacement means	On foot	

Table 10. Checking modified archetype **impulsive**.

second he does **not**. This is consistent with intuition, given that these type of fires are mainly accidentally caused by farmers.

- **Impulsive** is characterized by the starting point of the fire, which is a **road**, and the main use of the burned surface, which is **forestry**. As for **profit**, there is a **pattern** of action of the incendiary in the criminal activity. In this case, the arson has no specific objective beyond the arsonist momentum, so the forest is usually burned but not other types of surfaces. A road as starting point of the fire is characteristic in this archetype because it is a fast escape route after causing the fire.
- **Profit** is mainly characterized because the starting point of the fire is a **pathway**, and there is **no history of substance abuse** by the arsonist, which is logical from the point of view that, contrary to the previous archetypes, this type of wildfires are premeditated. The existence of a **pattern** of action is shared with **impulsive**.
- **Revenge** is the only archetype in which wildfire start time matters, and it occurs in the **evening**. Moreover, it is just the opposite as **profit** in the sense that for this archetype, there is **no pattern** of action but the author does have a **history of substance abuse**. This would tell us that usually this type of provoked forest fire is not the consequence of deliberate action, rather, it is carried out by a person under the effects of drugs and who could be swayed by an impulsive feeling of rage.

4. Conclusion

By using an ad hoc BN model learned from a dataset, we construct five archetypes for provoked forest fires. These archetypes are structured from arsonist motivation, which is the most central author variable in the model and plays an important role in psychological criminology, in accordance with the modes of operation in criminal activities of *Shye's model of action system* [33]. We see that the constructed model from the dataset of solved provoked Spanish forest fires conforms to this theoretical model. Two archetypes correspond to the mode of operation *adaptive*: **slight negligence** and **gross negligence**, which are distinguished in that while for the first the author stays at the crime scene and helps firefighting equipment, for the second he does not. The rest of archetypes are **impulsive**, **profit** and **revenge**, and correspond respectively to the modes of operation *integrative*, *expressive* and *conservative*.

In addition, we obtain a ratification of the five archetypes introduced in Sotoca et al. [11] in general terms, but with some specificities obtained thanks to the great potentiality of the used methodology. Indeed, the constructed BN models the relationships of dependency between the different variables (features of the wildfire and characteristics of the arsonist, including motivation), and it is precisely the understanding of these dependencies that allows to obtain predictions about some variables (queries) from others (evidences), without having to give up to take into account the complex relations that exist among them. As a matter of fact, the BN model captures these complexity and use it in an efficient way.

The specificities of each archetype are given by the values of a reduced set of variables that characterize each one, as stated in **Table 11**, where the confidence level or each archetype, which is the probability of the prediction given the corresponding set of evidences, is also consigned. As expected, the best results in terms of the predictive capacity of the model correspond to both types of negligence, which are the most common consigned motivations in the dataset, far ahead of the other three archetypes, much less frequent.

With this work we hope to highlight the usefulness of BN as an objective and quantitative methodology to obtain valuable information from the dataset, and its applicability in the study of criminal motivation and behavior in general and, in particular, of forest arsonists, helping to identify the authors and to study this phenomenon, so complex and with such serious consequences for the environment.

Archetype	**Evidence variables**	**Value**	**Conditioned distr. of A_{15}**	**CL**
(1) Slight negl.			Profit (0.87%)	98.92%
	C_4 = starting point	Crops	Gross negligence (0.00%)	
	C_5 = main use of surface	Agricultural	**Slight negligence (**98.92%**)✓**	
	A_{11} = stay in the scene	Gives aid	Impulsive (0.19%)	
			Revenge (0.02%)	
(2) Gross negl.			Profit (6.78%)	90.98%
	C_4 = starting point	Crops	**Gross negligence (**90.98%**)✓**	
	C_5 = main use of surface	Agricultural	Slight negligence (0.00%)	
	A_{11} = stay in the scene	No	Impulsive (1.69%)	
			Revenge (0.56%)	
(3) Impulsive			Profit (16.39%)	59.32%
	C_4 = starting point	Road	Gross negligence (5.60%)	
	C_5 = main use of surface	Forestry	Slight negligence (9.23%)	
	C_8 = pattern	Yes	**Impulsive (**59.32%**)✓**	
			Revenge (9.46%)	
(4) Profit			**Profit (**32.63%**)✓**	32.63%
	C_4 = starting point	Pathway	Gross negligence (10.75, %)	
	C_8 = pattern	Yes	Slight negligence (19.49%)	
	A_9 = history subst. abuse	No	Impulsive (31.79%)	
			Revenge (5.34%)	
(5) Revenge			Profit (5.22%)	51.81%
	C_3 = wildfire start time	Evening	Gross negligence (11.03, %)	
	C_8 = pattern	No	Slight negligence (4.10%)	
	A_9 = history subst. abuse	Yes	Impulsive (27.84%)	
			Revenge (51.81%**)✓**	

Table 11. Final archetypes: an improved and reduced version. The confidence level (CL) for each archetype is the probability of the outcome predicted for A_{15}.

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A. Appendix A

A.1. Learning the BN

For the learning process of the BN we adopt the *score-based* structure learning method (*"Greedy search-and-score"*), which is an algorithm that attempts to find the structure that maximizes the score function. We choose, as usual, the **Bayesian Information Criterion (**BIC) as score function, since it is intuitively appealing because contains a term that shows how well the model predicts the observed data when the parameter set is equal to its MLE estimation, which is the log-likelihood function, and a term that punishes for model complexity. This algorithm searches through the space of possible structures of the network; in each step, it considers the addition, elimination, or the reverse of an arc, given the structure of the previous step (with the constraint that the resultant graph be acyclic), and "greedily" choose the option that maximizes the score function, stopping when no increase is possible. In order to compute the score of the model in each step, this algorithm only needs to recompute few scores from the previous step (*local scoring updating*), which represents a huge calculation advantage. The problem with this algorithm is that we could obtain a solution that is a local (but not global) maximum of the score function. For that, we use the "iterated hill-climbing" algorithm, which carries out a local search until a local maximum is obtained, randomly perturbing it for then repeat the process. Finally, the maximum over local maxima is used as a better approximation of the global maximum.

A.2. Validation

We perform a cross-validation procedure, which is a technique for assessing how the BN model performs in the sense of correctly predicting a query variable (author variable) from an evidence given in terms of the variables of an independent (future) wildfire. That is, we want to estimate the accuracy in prediction in practice using our model. Concretely, we use *leave-one-out cross-validation*. Each round of the cross-validation procedure involves choosing a case (one different every time) and learn the corresponding BN model from the training set which is the complementary of the choosing case in the dataset, which is then used to validate the BN model. Indeed, for that case, we use as evidence the values of the crime variables $C_1, \ldots, C_{10}$ in order to predict each of the query variables $A_1, \ldots, A_{15}$, and take note of the matches between predictions and real values of these variables in the case. We perform, then, $N = 1597$ rounds of the cross-validation, one for each of the cases in the dataset. We take into account the matches over the N rounds in combination in order to estimate predictive accuracy for each of the author variables individually ("IPA" *Individual Predictive Accuracy* values), as well as globally ("OPA" *Overall Predictive Accuracy* value).

For each query variable, the IPA value is obtained by dividing the number of correct predictions by the total number of predictions (excluding blanks). The OPA value is obtained by dividing the total number of matches (10, 543) by the total number of predictions (excluding blanks), which is 18, 141. The result shows an OPA of 58.12%, that is, the 58.10% of times we predict correctly an offender characteristic. Note that in total $n \times N = 15 \times 1,597 = 23,955$ is the number of predictions (number of variables that are predicted multiplied by the number of cases in the dataset), but only 18, 141 of them are recorded, which are those in which the corresponding author variable outcome was **not** a missing value. Of these, 10, 543 match and the rest do not. Both the IPA and OPA values are recorded in **Table 4**.

From this table we can see which are the wildfire arsonist characteristics that are typically correctly predicted (IPA ≥ 70%): A_3, A_7, A_8, A_9, and A_{10}. Note that all the author variables are predicted correctly more often than simply by chance, taking into account the number of levels of each one. Then, they can be used to narrow the list of suspects in an unsolved wildfire. It should also be borne in mind that, as predictions are made with our model, we choose as prediction for a variable the outcome that maximizes the probability, causing failures in prediction when the second most likely outcome has a probability close to the first one, what is really happening with some of the variables, making the accuracy not as high as would be desirable.

Finally, we also compute the "DIPA" (*Disincorporate Individual Predictive Accuracy*), which is the percentage of correct predictions, for each author variable, according to the prediction that we made for it from the evidence given by the crime variables. For example, for A_{15}, the IPA (accuracy rate) is 56.36%. If the prediction for A_{15} were "slight negligence", what happens 60.38% of the times, then accuracy rate would be 61.29%, as consigned in **Table 12**, while if the prediction for A_{15} were "revenge", what instead happens only 0.75% of the times, this rate plummets to 20.00%. We note that the most popular prediction for A_{15} is "slight negligence", which is the type of motivation with which prediction is most accurate. At the opposite end, the less popular prediction is "revenge", which is the type of motivation with the less accurate prediction.

If prediction for A_{15} were…		**% Accuracy in predicting A_{15} (DIPA)**
Slight negligence	(60.38%)	61.29
Gross negligence	(22.51%)	47.67
Impulsive	(9.90%)	53.33
Profit	(6.46%)	41.05
Revenge	(0.75%)	20.00

Table 12. Disincorporate Individual Predictive Accuracy (DIPA) for A_{15}. For each outcome of A_{15}, the percentage of times that the prediction for A_{15} is that value is consigned in parentheses.

A.3. The final model

The final BN model is that obtained learning from the whole dataset with $N = 1597$ cases, after validation process. The corresponding structure is that given by the DAG in **Figure 1**.

It is known that the performance of the algorithms used for learning BN is unsatisfactory if the database set does not have a sufficiently high number of cases. When can we say that the number of cases is big enough? It depends on the number of nodes and on the size of their domain, which is the set of different possible instantiations of the set formed by all the nodes. Both, number of nodes and size of their domain, are known in practice. But the sufficiency of the number of cases also depends on the underlying probability distribution, which a priori used to be unknown.

Are our $N = 1597$ cases sufficient to learn the BN model? In order to study this issue, we generate subset samples of size ranging from $m = 25$ to $m = N$ in increments of 5, at random, and from each one we learn the model and compute the BIC score function. Then, we plot the BIC score as a function of the size of the subset sample (see **Figure 2**). In this case, before attaining N a saturation point is reached (approximately at 1250), from which the BIC score does not improve significantly by increasing the size of the subset sample. As a consequence, we can say that it does seem the number of cases of the database set is big enough to learn the BN.

B. Appendix B

In Section 3.2, we have discussed the main idea in constructing archetypes by illustrating it with a simple example. There we mentioned that it was very important to be cautions applying intuition since otherwise, we could naively make the following erroneous reasoning: since the prediction for C_4 is "crops" if A_{15} is any type of negligence, and "pathway" for the rest of

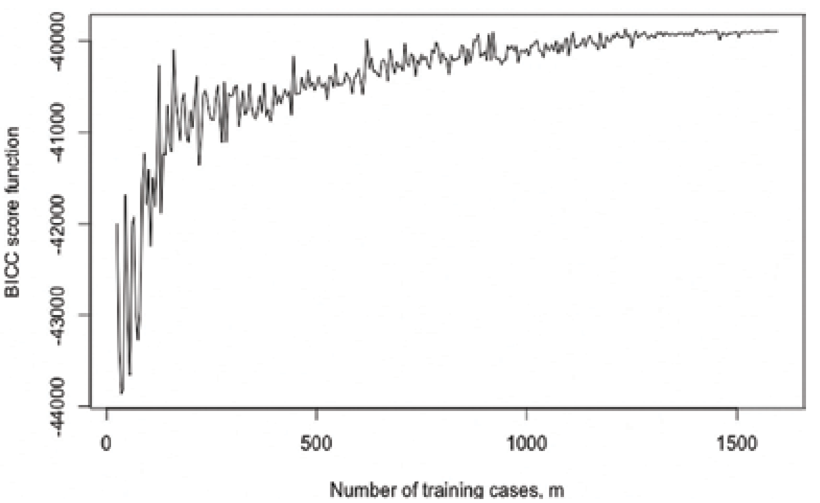

Figure 2. Evolution of the BIC score function as the number of training cases, m, increase to N.

values of A_{15}, as can be seen in **Table 13**, and since prediction for C_5 in both cases is "agricultural" (**Table 14**), then the prediction for C_5 would be the same, "agricultural", independently of the motivation. Actually this is not so. Indeed, since the geodesic joining A_{15} and C_5 has distance 2, passing through the only one intermediate node C_4, we can easily compute the probability of each value of C_5 conditioned to A_{15} from the CPT of C_5 conditioned to C_4 (**Table 14**), and that of C_4 conditioned to A_{15} (**Table 13**).

In this simple case it is possible to show the calculations, and we do it "by hand" to exemplify the procedure. For example, we can compute $P(C_5 = \text{"agricultural"}/A_{15} = \text{"slightnegligence"})$ by using the Conditioned Law of Total Probability in the following way, by conditioning to all the possible outcomes of C_4:

$$P(C_5 = \text{"agricultural"}/A_{15} = \text{"slightnegligence"}) =$$

$$P\big(C_5 = \text{"agricultural"}/C_4 = \text{"pathway"}\big)\,P\big(C_4 = \text{"pathway"}/A_{15} = \text{"slightnegligence"}\big)+$$

$$P\Big(C_5 = \text{"agricultural"}/C_4 = \text{"road"}\Big)\,P\Big(C_4 = \text{"road"}/A_{15} = \text{"slightnegligence"}\Big)+$$

$$P(C_5 = \text{"agricultural"}/C_4 = \text{"houses"})\,P(C_4 = \text{"houses"}/A_{15} = \text{"slightnegligence"})+$$

$$P\big(C_5 = \text{"agricultural"}/C_4 = \text{"crops"}\big)\,P\big(C_4 = \text{"crops"}/A_{15} = \text{"slightnegligence"}\big)+$$

$$P\big(C_5 = \text{"agricultural"}/C_4 = \text{"interior"}\big)\,P\big(C_4 = \text{"interior"}/A_{15} = \text{"slightnegligence"}\big)+$$

$$P(C_5 = \text{"agricultural"}/C_4 = \text{"foresttrack"})\,P(C_4 = \text{"foresttrack"}/A_{15} = \text{"slightnegligence"})+$$
$$P(C_5 = \text{"agricultural"}/C_4 = \text{"others"})\,P(C_4 = \text{"others"}/A_{15} = \text{"slightnegligence"}) =$$

$$\begin{aligned} &0.38 \times 0.10 + 0.18 \times 0.04 + 0.30 \times 0.07 + 0.75 \times 0.38 \\ &+0.20 \times 0.15 + 0.11 \times 0.05 + 0.22 \times 0.21 \cong 0.43 \end{aligned} \tag{6}$$

Similarly, we can find the rest of conditioned probabilities and write the CPT of C_5 conditioned to A_{15} (**Table 15**), which coincides with the product of matrices given by **Tables 14** and **13**, in

$C_4 \downarrow A_{15} \rightarrow$	Slight negligence	Gross negligence	Impulsive	Profit	Revenge
Pathway	0.10	0.11	**0.31**	**0.29**	**0.33**
Road	0.04	0.04	0.29	0.11	0.22
Houses	0.07	0.05	0.02	0.01	0.04
Crops	**0.38**	**0.35**	0.03	0.14	0.02
Interior	0.15	0.16	0.09	0.16	0.04
Forest track	0.05	0.07	0.14	0.16	0.27
Others	0.21	0.22	0.12	0.13	0.08
	1.00	1.00	1.00	1.00	1.00

Table 13. Conditional probability table (CPT) of C_4 to A_{15}.

C_5↓ C_4 →	Pathway	Road	Houses	Crops	Interior	Forest track	Others
Agricultural	**0.38**	0.18	0.30	**0.75**	0.20	0.11	0.22
Forestry	0.21	0.45	0.17	0.12	0.48	0.51	0.30
Livestock	0.29	0.18	0.09	0.11	0.26	0.28	0.27
Interface	0.07	0.18	0.34	0.01	0.03	0.01	0.12
Recreational	0.05	0.01	0.10	0.01	0.03	0.09	0.09
	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 14. Conditional probability table (CPT) of C_5 to C_4.

C_5 ↓ A_{15} →	Slight negligence	Gross negligence	Impulsive	Profit	Revenge
Agricultural	**0.43**	**0.42**	0.26	0.32	0.25
Forestry	0.26	0.27	**0.35**	**0.33**	**0.36**
Livestock	0.19	0.20	0.24	0.24	0.25
Interface	0.07	0.07	0.10	0.06	0.09
Recreational	0.05	0.04	0.05	0.05	0.05
	1.00	1.00	1.00	1.00	1.00

Table 15. Conditional probability table (CPT) of C_5 to A_{15} computed by using the conditional law of total probability.

this order. The highest probability in each column is in boldface and corresponds to the prediction for C_5 given each evidence in terms of A_{15}, as stated in **Table 8**. We can see that the prediction for C_5 is "agricultural" only if motivation is "negligence" (either slight or gross), being "forestry" otherwise.

On the other hand, for A_{13} the dependency chaining is more subtle and much more harder to follow *by hand*, so we give up on it and only carry out predictions by using the BN model with **R**.

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Section 2

Forest Fire Monitoring and Modelling

Chapter 3

Forest Fire Monitoring

Ahmad AA Alkhatib

Additional information is available at the end of the chapter

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Abstract

Thousands of hectares around the globe destroyed by forest fires every year causing tragic loss of houses, properties, lives, fauna and flora. Forest fires are a great menace to ecologically healthy grown forests and protection of the environment. This problem has been the research interest for years, and there are a number of solutions available to resolve this problem. In this chapter, a summary is given for all the technologies that have been used for forest fire detection with explanation of what parameters these systems looking for to understand the fire behaviour.

Keywords: forest fire detection, forest fire monitoring, forest fire system, forest fire behaviour, fire early warning systems

1. Introduction

Forests play a vital role in maintaining the Earth's ecological balance. Unfortunately, the forest fire is usually only observed when it has already spread over a large area, making its control and stoppage arduous and even impossible at times. The result is irreparable damage to the atmosphere and environment, where 30% of CO_2 in the atmosphere produced by forest fires [1, 2]. Among other consequences of forest fires are long-term disastrous effects such as impacts on local weather patterns, global warming and extinction of rare species of the flora and fauna.

Forests are vast remote abandoned areas, full of highly combustible material with dry leaves and branches to the Earth surface composites, where these are perfect to act as a fuel source for fire ignition and later fire stages. The fire ignition may be caused through human actions or by natural reasons. The initial stage of ignition is normally referred to as "surface fire" stage. This may then lead to feeding the fire flame, thus becoming "crown fire." Mostly, at this stage, the fire becomes uncontrollable, and the damage to the landscape may become excessive and could last for a very long time depending on prevailing weather conditions and the terrain.

2. Problem size

Forest fire is a global environmental problem causing extensive damage every year. According to International Union for Conservation of Nature (IUCN) Report "Global Review of Forest Fire 2000," wild fire is a natural phenomenon. However, over 90% of all wildland fires are due to human action causing significant forest loss, that is 6–14 million hectares of forest per annum, and 30% of the CO_2 in the atmosphere produces from forest fire. This leads to enormous economic losses, damage to environmental, recreational and amenity assets, global warming and loss of life. There is a strong recognition that action is needed to catalyse a strategic international response to forest fires [3].

2.1. In the case of the USA

In the 2003–2004 wildfire sieges, CAL FIRE's fire suppression costs exceeded $252.3 million; property damage costs exceeded $974 million; 5394 structures were destroyed; and more than 23 people lost their lives as a result of California wildfires. "Increasingly destructive wildfires are ravaging homes and businesses in more than three-fourths of the states. One of the most devastating fires in recent history was the $1 billion Witch Creek Wildfire that decimated vast parts of San Diego County, California, in October 2007. By the time it was fully contained, the fire had burned an estimated 198,000 acres and damaged or destroyed more than 1200 homes and 500 outbuildings."

In terms of scale, the 2007 fire season was second only to last year in acres burned and costs expended. In 2007, there were 27 fires costing over $10 million whose total suppression cost approached $547 million, exclusive of burned area emergency rehabilitation costs. These fires alone accounted for just less than 3 million burned acres. All wildfire acres reported to the National Interagency Coordination Centre in calendar year 2007 totalled 9.32 million acres at a federal cost of approximately $1.8 billion. On 17 June 2002, an estimated $9,403,000 was spent battling 196 wildland fires that scorched over 51,000 acres of land in parts of 11 states in the USA [4].

Hundreds of thousands of acres is burnt within the wildland urban interface (WUI) each year. Each year, over $100 million is spent on suppression efforts and more in the disaster recovery phases of catastrophic, natural and/or human-caused hazards, but the losses continue to mount.

2.2. In the case of Canada

Canada has approximately 10% of the world's forests. However, about 7400 forest fires have occurred in Canada every year over the last decade, burning an average of 1.9 million hectares of forests. In British Columbia alone in 2006, which was not a peak fire year, there were 2590

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forest fires destroying 131,086 hectares and costing $156 million. Fire suppression expenses during the last decade in Canada have exceeded the $500 million and almost hit the $1 billion a year. [Facts about Wildland Fire in Canada, 2012.] On 5 October 2009, for example, a huge fire in the San Bernardino National Forest, CA, burned 3500 acres. More than 500 firefighters found it hard to control due to the strong 72 km/h wind speed [5]. The story continued year after year in Canada (see **Table 1**).

2.3. In the case of Europe

On 14 August 2012, the following report was published in *ScienceDaily—'the 2012 fire season has been characterized by a high number of fires in the early season. Over 100,000 hectares had already been consumed by fire at the end of March. July brought critical fire episodes in Spain and Portugal, which led to a number of human casualties'.*

There was a high fire risk in southern Europe during the last period, specifically in France, Portugal, central and southern Italy, the Balkan region, Spain, Greece and Turkey.

The European Forest Fire Information System (EFFIS) provides monitoring and fire mapping, regular forecasts for fire danger up to 6 days in advance and provides near-real time estimations for fire damages across Europe.

Until present, almost 580,000 hectares, in the area monitored by EFFIS, have been burnt this year, which includes Europe, North Africa and Middle East countries [ScienceDaily 2012]. In August 2009, forest fires wreaked havoc in Greece (3700 acres, hundreds of houses). Also in 2007, there was a terrible fire in Greece.

Year	Number of fires	Number of hectares burned	Total cost (millions)
2006	2590	131,086	$156.0
2005	976	34,588	$47.2
2004	2394	220,516	$164.6
2003	2473	265,050	$371.9
2002	1783	8539	$37.5
2001	1266	9677	$53.8
2000	1539	17,673	$52.7
1999	1208	11,581	$21.1
1998	2665	76,574	$153.9
1997	1175	2960	$19.0
1996	1358	20,669	$37.1
1995	1474	48,080	$38.5

Table 1. Forest fire in Canada [5].

2.4. In the case of Australia

On 21 November 2009, in Tasmania, Australia, a horrible forest fire was reported [5]. Some of the fires could be natural disasters or directly or indirectly the product of human negligence and abuse of the environment (including the rise of temperature associated with the global warming).

"In February 2009, Victoria was devastated by one of the worst bushfires in Australia's history. The Black Saturday fires caused many deaths and injuries and directly affected many towns and communities, destroying homes, businesses, schools and kindergartens. Key statistics from the Victorian Bushfire Reconstruction and Recovery Authority are:

- deaths 173
- area burnt 430,000 hectares (including 51 towns, 78 communities)
- total property dollar losses $1.35 billion
- homes lost 2129, valued at $713 million (includes contents and buildings)."
- Too many horrible fires occurred in Australian history, probably that resulted from its nature.

2.5. In the case of the UK

South Wales Fire and Rescue Service cover an area of 2712 km squared, which is divided into 10 "Unitary Authorities": Bridgend, Vale of Glamorgan, Rhondda, Cynon Taff, Cardiff, Caerphilly, Merthyr, Blaenau Gwent, Torfaen, Newport and Monmouthshire, where a population of 1.4 million covered by their services [6].

The Welsh society statistics provided by the Fire and Rescue Services of Wales continues to be high. It shows that, in purely economic views, the expenditure to Wales's areas in years 2006 and 2007 was £56.3 million. In South Wales area alone, the cost was about £35.2 million.

Figure 1. The aim of forest fire monitoring systems.

Forest fire monitoring systems can help in fire suppression. The fire department will receive the information and evaluate the situation. The known rules apply here: 1 min—1 cup of water, 2 min—100 liter of water, 10 min—1000 liter of water. The main aim of the systems is shown in **Figure 1**.

3. Overview of forest fire behaviour

Let us define the fire first:

"Combustion is a complex process in which fuel is heated, ignites, and oxidizes rapidly, giving off heat in the process. Fire is a special case of combustion—self-perpetuating combustion characterized by the emission of heat and accompanied by flame and/or smoke. With fire, the supply of combustible fuel is controlled by heat given off during combustion" [7]

Fire requires three components: fuel, heat and oxygen to be present. If one of the factors is missing, the fire will go out. There must be (**Figure 2**):

1. a source of fuel for combustion,
2. a source of heat to promote the reaction (the fire itself),
3. oxygen in fair concentration to maintain the reaction.

A forest fire is a dynamic phenomenon that changes its behaviour in time. Fire spreads through forest fuel. It is performed by a complex heat transfer and thermo chemical processes that determine fire behaviour [8].

There is more than 27 mathematical models defined to describe the forest fire behaviour; each model was built according to different experiences in different countries with forest fire. Every model differs from the others according to the input and the environmental parameters (fuel indexing [9, 10]). Researchers in some countries manage to use some of these models in simulation programs or even create their own methods for mapping the landscape and the fire behaviour on monitoring screens for analysis and expectation of fire behaviour to help the firefighters to determine the best method to extinguish the fire such as BehavePlus, FlamMap,

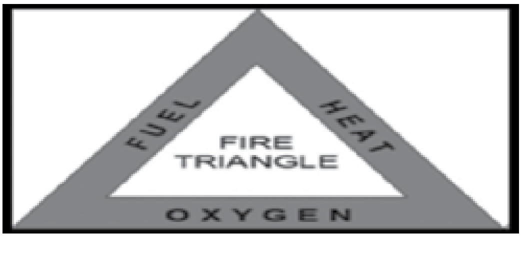

Figure 2. Fire triangle factors [7].

FARSITE, Geodatabase and ArcSDE. On the other hand, researcher's target is to find a reliable technology that can detect and localise the fire, help in decision-making of crisis possibility or a high fire risk situation. As a result, the fire can be extinguished in early stages within a short time to minimise the damage save lives, environment, firefighter equipment, time and effort.

A wildfire burning in constant environment takes the shape of an ellipse. Environment can be a variable of time. A fire might have different parts burning in different environments, such as moisture contents, wind speed, wind direction, slope and so forth. The environment heterogeneity might result in a very complex fire shape [7, 9] (**Figure 3**).

The fire parts are shown in **Figure 4**:

- A finger is a long, narrow extension of the main body of fire.
- A pocket is an unburned indentation of the fire perimeter surrounded on three sides by the fire.

Figure 3. Fire elliptical shape under constant environment.

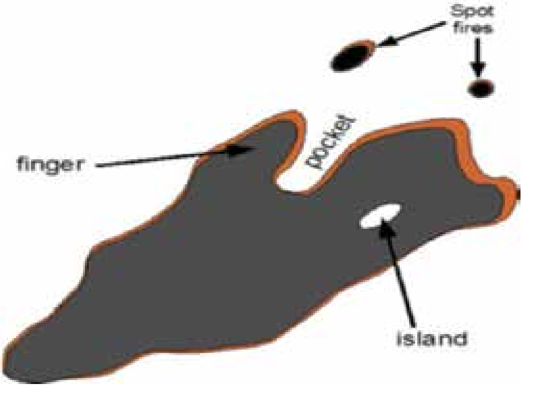

Figure 4. Parts of fire [7].

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- An island is an unburned area surrounded by burned area within fire.
- A spot fire is a fire initiated outside the main fire.

These parts have no reference scales. For example, a finger might be one foot long or may exceed a one mile. Fingers might have fingers and spots might have spot fires.

The direction of the fire spread has two parameters: the maximum spread direction and long axis of the ellipse, as shown in **Figure 5**. The relative direction is the angle between the front flame orientation and the maximum spread direction.

Three types of fire propagation are as follows: ground fire, surface fire and crown fire. The perfect fire environment is a forest full of trees and shrubs, to start with surface fire then extend it through the tall trees to crown fire. At this stage, the fire will start to propagate, and it becomes hard to extinguish (**Figure 6**).

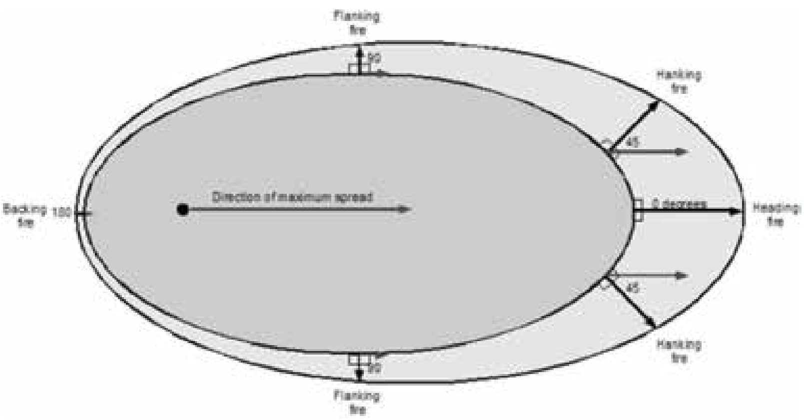

Figure 5. Fire spread directions [7].

Figure 6. Crown fire.

4. Monitoring systems

The information produced from monitoring can help the firefighters to understand the fire behaviour such as point of ignition, the spread speed and the direction of maximum spread. These parameters can be used as input for fire simulation programme to help extinguishing fire and provide safety to firefighter. Team work is very important for fire fighting to optimise the work with minimum efforts, minimum damage and the shortest time, for example, if the fire spread direction endangers human areas, the team priority target is to stop the propagation in that direction, so more firefighters should focus in that direction. On the contrary, to extinguish the fire with the shortest time, more firefighters can focus the team work on the mother/main fire not the finger to weaken the front flame, reduce the fire intensity, limit the spreading, reduce the dangerous and make it easier to extinguish (**Figure 7**).

4.1. Fire suppression authorities and detection techniques

The common techniques used by authorities for fire detection and suppression [1]:

i. controlled/supervised burning,

ii. fire and weather casting and estimation for the fuel moisture level,

iii. human watchtower,

iv. optical smoke detection,

v. light detectors to detect and coordinate strikes,

vi. infrared,

vii. spotter planes,

viii. water tankers,

ix. mobile/smartphone calls.

Detection and monitoring systems are divided into two main groups:

a. volunteer reporting-public reporting of fires, public aircraft and ground-based field staff,

b. operational detection systems: fire towers, aerial patrols, electronic lightning detectors and automatic detection systems.

Figure 7. Fire management.

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Many techniques used in fire suppression in different countries, like using flying water tankers like in Canada and burning dry region under the supervision of fire fighters rather than having a crisis later. Other countries sweep away the surrounding area to stop spreading and isolate it as in the Middle East. Australian authorities sometimes leave the fire to burn, until it dies alone, if it causes no harm for humans or properties.

4.2. Satellite system

Earth-orbiting satellites and even air-floating devices have been employed for the observation and detection of forest fires. Satellite images generated mainly by two satellites launched specifically for forest fire detection purposes—the advanced very high resolution radiometer (AVHRR) [11] launched in 1998 and the moderate resolution imaging spectroradiometer (MODIS) [12] launched in 1999—have been used. These satellites can provide images of the Earth once every 2 days and that is a long delay for fire scanning; in addition, the quality of satellite images depends on weather condition [13].

Any satellite-based observation for forest fires suffers from severe limitations resulting in a failure in the speed of detection or the quality or the running cost to produce effective control for forest areas. Some limitations in observation of forest fires from geostationary (GEO) or Low Earth Orbit (LEO) satellite are as follows: it is impossible to provide a full coverage by using satellite monitoring. GEO and LEO satellites are located on orbits over 22,800 miles above the Earth's surface. Infrared radiations emitted by fire flames may be too feeble in intensity to be detected by satellites at early stage. The intensity of radiation decreases with the square distance, and the radiation beam angle of arrival in regards to the surface of the detector or camera. However, satellites are not the best choice to detect the forest fires at early stages.

Some satellites might not be equipped with detection of forest fires, such as transponders, frequency translation, amplification reception, regeneration, antennas and downlink transmission. In fact, formal allocation for appropriate frequency and bandwidth for forest fire detection purposes is not available yet.

4.3. Optical sensor and digital camera

Camera surveillance and wireless sensor network are the other available techniques for forest fire detection. The technology advancement of cameras, image processing, industrial computers and sensors resulted in advance automated for early warning systems. Many types of detection are used in terrestrial systems [14]:

- **i.** video camera system is able to recognise a spectrum of smoke and fire during day and night.
- **ii.** thermal cameras detect the heat glow of fire.
- **iii.** IR spectrometers are used for the identification of spectral characteristics of smoke
- **iv.** LIDAR (detection of light and range) systems measure reflected laser rays from smoke particles.

All variety of optical camera systems used different algorithms designed by experts, where all rely on the same general concept (smoke and fire glow detection). In general, cameras capture images every certain time, where images are number of pixels. The image-processing unit (1) tracks motion between sequenced images and (2) checks and compares pixels that contain smoke or fire glow. Then the results used in another algorithm to make a final decision whether the current situation requires action. Optical systems are integrated with geographical maps for localisation purposes (see **Figure 8**).

Use of a given type of camera or sensor depends not only on the specific conditions of the operation but also on the financial resources available. The following are some available systems in the market:

AlarmEYE is a video and infrared camera system used for to detect early forest fire. It is based on black and white colour frequency where the infrared filter can distinguish between heat vapour and flames. This system was produced and deployed in Thailand [16].

EYEfi SPARC. Optical sensors are produced by EYEfi, Australia, for forest fire detection. Optical sensors consist of:

i. camera (ultralow light grey scale at night and colour during the day)

ii. lightening detection sensor

iii. communication unit

iv. weather station

v. power system

vi. tilt zoom cameras can be added to the system

EYEfi cannot provide a smoke detection, but it is on the future plans. Simply, EYEfi can play a helping role in providing images for fire agencies after the operator spots smoke by using the

Figure 8. ForestWatch system [15].

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EYEfi software and GIS map to localise the smoke position on the ground. A weather station and lightening detector are included in the system for more accuracy [14, 16].

UraFire system focused on reducing the number of false alarms by identifying smoke based on two inputs: (1) clustering motions and (2) a time input. The UraFire system is used and produced in France [14, 17, 18].

Forest Fire Finder is a unique, smart and complicated system based on atmosphere analysis instead of detecting fire glow or column of smoke. Forest Fire Finder tracks the way the atmosphere absorbs the sunlight. Naturally, the absorption depends on the chemical molecules or composition in the atmosphere. Different composition has different absorption behaviours; therefore, Forest Fire Finder can define different kinds of smoke based on the source in a range of 15 km, such as the organic smoke from burnt trees and the industrial smoke. The equipment installed in tree crowns for faster detection, and this system is used in Portuguese forests [16, 19] (see **Figure 9**).

ForestWatch is an optical system based on sensor cameras, which provide a semiautomatic fire detection produced by Enviro-Vision Solutions, South Africa. The camera tower scans the forest in a range of 16–20 km for a column of smoke during day and fire glow during night. [20, 21]. ForestWatch consists of [15]:

i. a 360° Pan tilt cameras to allow +33 to −83 tilt from horizon, with 24× optical zoom,

ii. telecommunications system such as microwave, 3G or satellite,

iii. image sampling engine,

iv. processing software to evaluate the current situation.

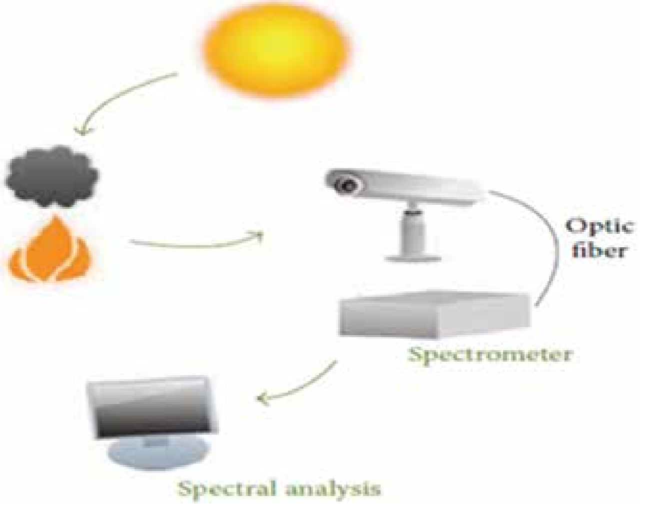

Figure 9. Forest fire finder.

The most popular system in forest fire detection is ForestWatch. On the contrary, only Canada has documented its own experience with the system. Canada pointed that fires were detected in a range of 20 km reliably, but a large number of faulty alarms were also generated. Operational ForestWatch systems are in use in the USA (22 towers), Canada (4 towers), South Africa (83 towers), Chile (20 towers), Swaziland (5 towers) and Slovakia (4 towers). A pilot scale operation (2 towers) is installed in Greece [20, 21].

FireWatch has been studied for years (since 1992) in Germany, and now it is produced by German Aerospace Institute (DLR). It is an automatic smoke detection within a range of 10–40 km. FireWatch systems are used in Estonia (5 towers, 1 control room), Germany (178 towers, 22 control rooms), Mexico (1 tower, 1 control room) and Cyprus (2 towers, 1 control room). Pilot systems (1 or 2 towers) are in use in Italy, Czech Republic, the USA, Spain, Greece and Portugal [20]. FireWatch components consist of [22]:

i. Optical sensor system (OSS): the optical system performs a 360° rotation once every 4–6 min during day and 8–12 min during night in 10-degree steps.

ii. Data transfer: wireless connection between OSS and officer computer.

iii. Central office: the work space/area (computers, monitors and printer) (see **Figure 10**).

FireHawk. A risk management system that can localise fire consists of the following layers [14]:

i. imaging layer: represents cameras installation on suitable positions,

ii. communication layers: wireless links,

iii. machine vision layer: FireHawk uses the GIS and the ForestWatch software to localise and find the shortest path to the fire. FireHawk is deployed in two areas in South Africa.

The Bushfire Cooperative Research Centre in collaboration with the Australian government published a very interesting report about the experience of using three optical systems. The target is to testify the performance of each one of the systems compared to normal human

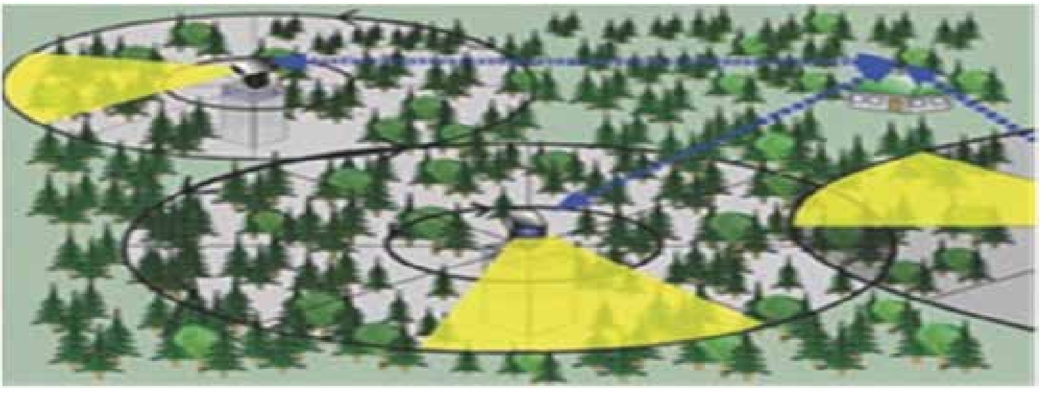

Figure 10. FireWatch [22].

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observation towers [20]. The report provides full details about the project, environment, experiment, analysis and results. The three systems used in this project are FireWatch, EYEfi and ForestWatch in 2010, all of which had been tested on three kinds of fires: agency burning, private burning and research burning in Otway Ranges in Victoria and Tumut in NSW (see **Figure 11**).

Some of the results explored on the NSW trials are shown in **Table 1**:

i. More than 250 private fires were reported in the study area. A high proportion of them were reported by observation towers not by cameras.

ii. Thirty-seven prescribed fires and burn-off fires were conducted as part of land management tasks during the post fire season in NSW forests, National Parks and Wildlife Service and Victorian Department of Sustainability and Environment. One unplanned bushfire was reported in Victoria and none in NSW.

As a result of this project, the trained human tower observer is more reliable and faster than the three systems together, and it is not possible to rely on optical cameras only. However, it might be useful to improve the performance of human observer or cover unstaffed tower or remote areas. They indicate that FireWatch detected more fires than the other systems and the only system to report the forest burns, although the detection was 35 min later than the human tower detection and the fire was five times bigger. The system performance was partially a function of distance from camera and the size of the fire; moderate burns (10–20 km) were missed while large burns were detected at long distances (70 km). The systems are not able to take landscape topography in calculation, which leads to misallocation of the fire. The causes for that are shown in **Figure 12**.

They concluded the report with the following points.

i. Cameras are not suitable replacements for trained human observation tower.

ii. Human towers and optical systems were used for forest fire scanning for column of smoke. There is a delay between ignition time and a noticeable column of smoke that can be detected by optical cameras or human.

iii. Landscape appearance, atmosphere conditions, and the properties of the smoke are different from one country to another.

Figure 11. Tower in Tumut, Australia, with the three systems [20].

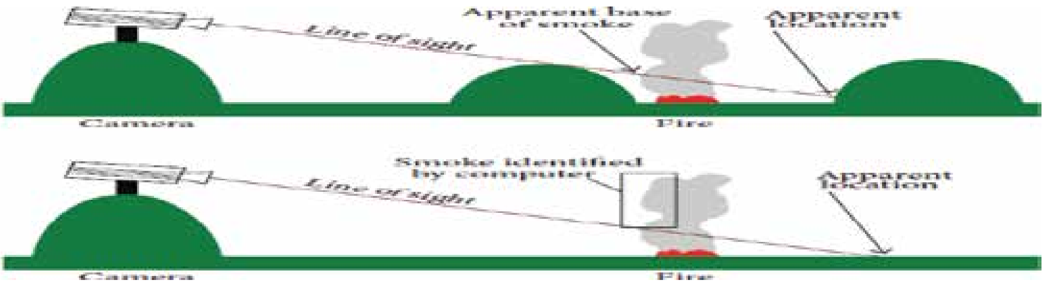

Figure 12. Localisation error reason [20].

Optical systems require more improved and intelligent algorithms and techniques in regard to the number of faulty alarms caused by various dynamic phenomena such as reflections, wind-tossed trees, human activity and cloud shadows. Processing landscape images is very difficult due to nature variety and to the dynamic events that may cause various illuminating, which depends on distance, weather, masking objects, time of day and so forth. These events produce dynamic envelopes, which are not always caused by motion and consist of time-varying grey levels of connected pixels in several image regions.

Optical cameras are designed to cover large areas (in a range of 15–80 km) with a minimum number of camera towers, and they can only provide a line of sight vision, which is a problem in the forest areas, as hills, high trees and mountains might block the vision. Weather condition and night vision reflect on the camera performance.

Camera surveillance technology with short distance links was also tried, despite the need for manual installation for every camera in a suitable position. Still the line of sight images, bad weather image, night images and high probability of false alarms for the following reasons: (1) daily motion of the Sun, (2) vegetation, (3) variation of atmospheric extinction and (4) moving clouds.

Finally, optical systems are extremely expensive; optical tower might worth more than $30,000 per tower, and there is a need to build these towers and install a communication infrastructure in the remote areas inside the forests.

4.4. Wireless sensor network

The line of sight problem of optical cameras in forests can be solved with the second type of sensors. A new technology called wireless sensor network (WSN) can be deployed in large number of systems, one potential application is forest fire detection. The same printed circuit board integrates the wireless transceiver, sensors and data processing. Sensors are able to influence the physical parameters such as pressure, temperature, gases, radiations, humidity and many other parameters. Sensor network normally deployed in a large-scale random distribution on remote or inaccessible places and under harsh environment for a certain period of lifetime. This technology relied on low data rate and short ranges of communication with multi-hope fashion to reach the sink.

The recent advancement in sensor network technology has made it possible to use this technology in early forest fire detection. A number of studies have considered using WSN in wood fire systems.

Spain used a sensor network and IP cameras to detect the fire ignition by sensors and use the closest camera to provide images for fire. Spain tried four IP cameras where they installed manually in the forest and images are heavy load on such a limited resources network such as sensor network [23].

Forest Fire Surveillance System (FFSS) is a South Korean system. The surveillance is done by sensor network to observe illumination, temperature and humidity. These readings go into a database to make a daily calculation and comparison in order to evaluate the hazards [24].

FireWxNet is a system target to study the forest fire behaviour not detection. The system uses wireless sensor network to provide data for weather status and web cameras to provide images for the fire. The system uses a tiered structure, which starts with directional antennas on the top of mountains and ends with multi-hope sensor network to observe the required environmental parameters. They used web cameras to provide vision data as well, and they equipped the sensors with a small GPS device to provide the location information (see **Figure 13**) [25].

It is a very smart system proposed in Canada. The system based on fire weather index (FWI) to calculate the probability of fire and the spread speed of the fire. The model provides the fire probability, spread speed, weather observation, moisture content and the fuel codes, which is divided into the following three types to describe the soil content of forest ground [26].

i. Fine Fuel Code (FFMC) represents the litter and fine fuels for 2 cm deep.

ii. Duff Moisture Code (DMC) represents moisture content of decomposing organic material for 5–10 cm deep.

iii. Drought Code (DC) represents the moisture organic content for 10–20 cm deep (see **Figure 14**).

It is a Forest Fire Detection project in Pennsylvania [27]. The system uses fire sensors and GPS devices. The project has two aims: (1) rely on the existing technology and (2) replace all the existing fire detection techniques with more efficient ones.

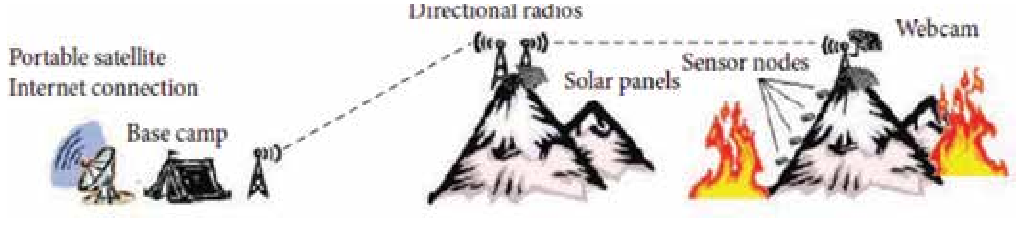

Figure 13. FireWxNet [25].

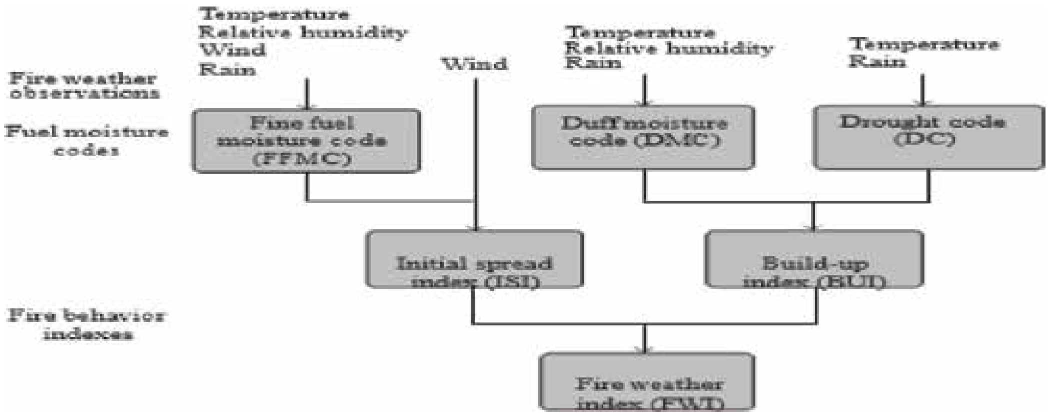

Figure 14. FWI system [26].

The project plan is to install 12,000 units within 48 months, 4000 devices every 12–15 months. When the sensor detects fire or smoke, a signal is sent through GPS device to Satellite, and then Satellite will forward the signal to monitoring screen and other handheld devices (see **Figure 15**).

Inner magnolia forest fire research has been done by a system of three parts: (1) monitoring, (2) information management and database system and (3) decision-making system. The system provides a fire simulation from the field images in 3D maps by using Geodatabase and ArcSDE programs for fire simulation [28].

FIRESENSE (Fire Detection and Management through a Multisensor Network for the Protection of Cultural Heritage Areas from the Risk of Fire and Extreme Weather Conditions, FP7-ENV-2009-1-244,088-FIRESENSE) [29] is a Specific Targeted Research Project of the European Union's 7th Framework Program Environment (including climate change). The FIRESENSE FP7 is a target to monitor remote areas and provide warning system. FIRESENSE is a very advanced system; it relies on IR, optical, temperature sensors, PTZ cameras and weather stations. All these sensors collect and process data to provide a clear understanding for the event to the local authority. The project deployments will be in Turkey, Italy Tunisia and Greece (see **Figure 16**).

Figure 15. Pennsylvania project [27].

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Figure 16. FIRESENSE FP7.

FP7 relies on complicated models, algorithms, concepts and comparisons. They are given as follows:

i. Scene model (Planck's radiation formula): the heat flux, thermal emitting, smoke, the fire, the reflectance, flickering, absorption emission lines, analysis of the atoms (e.g. potassium) and the molecules (water and carbon dioxide) are characteristics to be investigated.

ii. Thermal heat emitted from the background, sunlight reflection, clouds shadow, the buildings and the sky polarisation.

iii. Atmosphere gases (N2, O_2, CO, CO_2, H_2O, etc.); each gas behaves and absorbs differently; water vapour concentration; carbon dioxide is more uniformly distributed—its value is larger over industrial cities and vegetation fields than over oceans and deserts. **Figure 17** shows the physical aspects related to forest fire detection.

Libelium [30] is a Spanish wireless sensor network company. They named their product Waspmote and proposed it for many WSN applications such as forest fire detection, smart cities, water pollution and many other applications. With regard to forest fire detection, they used Waspmote nodes equipped with GPS device for localisation, and gas boards to measure temperature, carbon dioxide (CO_2), carbon monoxide (CO) and humidity for detection. Libelium deployed 90 nodes with solar panels for power scavenging to measure parameters every 5 min (see **Figure 18**).

Figure 17. How FIRESENSE analyse images [29].

Figure 18. Waspmote and gas board [30].

Wireless sensor network technology usually deployed in large number that can observe and the surrounding environment, transforming it into electrical signals, to send to the sink in a multi-hop fashion for processing. By this way, there is no need to build towers or set up complicated communication links such as microwave and satellite. WSN works on short communication links fashion and can provide real-time monitoring, where using this technology for forest fire application requires a large number of randomly deployed nodes to provide a reliable network if the key issues were addressed for this network: (1) localisation, (2) coverage, (3) network life span and (4) fire detection method.

5. Summary of existing techniques

- The first technique is human observation towers, but this technique is inaccurate and inefficient.
- Optical systems were used in many countries, and they also proved inefficiency due to camera manual installation and line of sight and night images problems.
- Satellite scanning is mainly done by two satellites: the Advance Very High Resolution Radiometer (AVHRR), launched in 1998, and the moderate resolution imaging Spectroradiometer (MODIS), launched in 1999. A full scanning for the Earth requires 2 days, which is considered long delay to detect the fire. Satellite images quality is related to weather conditions.
- Finally, WSN started to be considered as a partial solution, where this kind of technology is used together with other technologies such as IP cameras, weather databases and fuel databases.

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Chapter 4

Forest Fire Model

Saiful Bukhori

Additional information is available at the end of the chapter

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Abstract

Forest fire model is one of the dynamic system models that used cellular automaton paradigm. In this chapter, we discuss the forest fire model and how to implement in the serious game of real time gross settlement (RTGS) and the serious game of supply chain management (SCM) agroindustry.

Keywords: forest fire model, cellular automaton, real-time gross settlement, supply chain management

1. Introduction

Forest fire model is any of a number of dynamical systems displaying self-organized criticality (SOC). This model is defined as a cellular automaton on a grid with L_d cells. L is the side length of the grid and d is its dimension. A cell can be empty, occupied by a tree, or burning. The controlling parameter of the model is p/f, which gives the average number of trees planted between two lightning strikes [1].

Dynamic system theory is part of the field of mathematics used to describe the behavior of complex dynamic systems that can be easily analyzed. Dynamic system theory is usually by applying differential equations or difference equations [2].

The differential equation is a mathematical equation for a function of one or more variables, which links the value of the function itself and its derivatives in various orders. Differential equations play an important role in engineering, physics, economics, and other disciplines. Differential equations are used when a deterministic relationship involving a quantity that changes continuously, and the rate of change is known or postulated [3]. The problem that occurs is if continuous data changes are not known.

The basic idea to solve the problem is to consider a system with changes that are considered discrete. One example is the process of cell division that changes continuously but can only be observed in certain time series. The key here is that there is a relatively short and synchronized action that lets one ignore the behavior in the time period for the purpose.

Another alternative to discrete models is the discretization of the continuous time model. That is, we cannot really observe changes constantly, so we only monitor some data at discrete intervals. An example is an individual location (which constantly moves, but we can only observe at discrete intervals). This is the basic idea of time series analysis, which is a statistical approach to describe, predict, and control time-dependent system behavior.

Difference equations are discrete dynamic systems. When a variable time goes over a discrete set of intervals and continued for another interval, it will generate a dynamic equation in the time scale [4]. Some situations can also be modeled by a mixture of operators, such as differential.

Dynamical systems theory is a field of mathematics that used to describe the behavior of the complex dynamical systems. Dynamic system theory usually applies differential equations or difference equations. Dynamic system theory is called a continuous dynamic system if the system uses differential equation [5]. Continuous dynamical systems, from a physical point of view, are generalizable with classical mechanics. The implementation of continuous dynamical systems is generally postulated directly, which is not limited by the Euler-Lagrange equation. Dynamical system theory is called a discrete dynamic system if the system uses a difference equation. When the time variable runs over a discrete set for several intervals and continues over another interval, it will get dynamic equations on a time scale. Some situations can also be modeled by mixed operators such as differential difference equations.

The dynamic system, at any given moment, has a state represented by a tuple of real numbers that can be illustrated by a point in the appropriate state space. Dynamic system rule changes are functions that represent predictions of future circumstances based on the real data of the present situation. The dynamic system function is often a deterministic function, at certain time intervals, only one future state follows from the data of current state. However, some systems are stochastic, and functions in those random events also affect the evolution of the state variables. In order to make a prediction about the system's future behavior, an analytical solution of such equations or their integration over time through computer simulation is realized.

The dynamic systems that discussed in this section focus on dynamic system theory. Dynamic systems theory can be applied to various fields of science such as mathematics, physics, biology, chemistry, engineering, economics, and medicine. Dynamical systems are a fundamental part of chaos theory, logistic map dynamics, bifurcation theory, the self-assembly process, and the edge of chaos concept. In this section, we give examples of the application of dynamic system theory with probabilistic cellular automata forest fire models approach in real time gross settlement (RTGS) and agribusiness.

2. Cellular automaton

The world is not static, and the system is always changing over time in accordance with its importance. As the system changes, the value representing the state of the system in a

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particular phase also changes. The dynamic system is a phase along with rules governing how values represent the developing state. The path tracked out of phase space by evolution is called orbit. In order for the system to be a dynamic system with the above-mentioned definition, we require that the future state of the system must be fully determined by the state of the current system.

Chaotic condition is a condition where the system is dynamically growing [6]. In a system that has a chaotic condition is required a fairly complicated method to predict the next conditions, but predictions are a very important to determine a decision taken by an organization. The chaotic state of a system is mostly due to the initial conditions and dynamic rules that are difficult to determine accurately so as to influence the prediction of subsequent conditions.

Although the initial conditions are difficult to determine accurately, these conditions will affect how the system evolves, which means that the system does not really grow exponentially. With the growth conditions that are not really exponential, then the prediction to see the next step is an interesting activity to be studied.

Cellular automaton paradigm is very interesting because it can simplify complex problems. The arrangement of cells that describes the state in each time period is governed by simple local rules. Simple local rules proved to be the best way to analyze many natural phenomena. This is because most natural processes themselves are local. For example, molecules interact locally with their neighbors, bacteria with their neighbors, ants with theirs, and people likewise. Although the natural phenomenon is continuous, the automaton paradigm that tests the system using discrete time steps does not reduce the strength of the analysis. Therefore, in the artificial cellular automaton world, we have a microcosm that can be developed in the real world.

A cellular automaton is a mathematical model for systems in which many simple components act together to produce complicated patterns of behavior [7]. One-dimensional cellular automaton is a simple cellular automaton. The simple cellular automata has two possible values for each cell (0 or 1), and a rule that only depends on the value of the nearest neighbor. As a result, the evolution of elementary cellular automatons can be described completely by a table that determines the state of a cell given to the next generation based on the value of the cell to its left, the value of the cell itself, and the value of the cell to its right as shown in **Figure 1**.

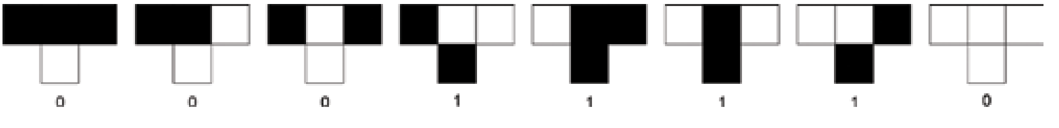

Figure 1. The simple cellular automata.

3. Agent-based model

The agent-based model has become increasingly used as a modeling approach in social science. This model is widely used because a person in his or her social life can build models with individual entities and their interactions [8]. When compared to a variable-based approach that uses structural equations or when compared to system-based approaches that use differential equations, agent-based simulations provide the possibility of modeling individual heterogeneity, which represents explicitly agents' decision rules and assigns agents to locations in geographic types or any other type of space. This condition allows the modeler to naturally represent some scale of analysis, the appearance of structures at the macro or community level of individual action, and different types of adaptation and learning. Approach to agent-based model is difficult to do with other modeling approach.

3.1. The agent-based model for real time gross settlement (RTGS)

In general, the RTGS transaction mechanism is performed by participants who send a payment transaction message to the central of management RTGS system located at the central bank for settlement process [9]. The mechanism at clearing house is a transmitter client who sends a message of transaction through transmitter bank, that having canal at clearing house, then continue to receiver client through receiver bank as shown in **Figure 2**.

Figure 2 shows that the transmitter client sends the funds through the transmitter bank by sending transaction messages through the channel on the clearing house (B11). From channel B11, the transaction information proceeds to the bank receiver and proceeds to the receiver client via channel on clearing house owned by its neighbors (B12, B13, B21, B22, B23, B31, B32, and B33) using the forest fire model concept [10] .

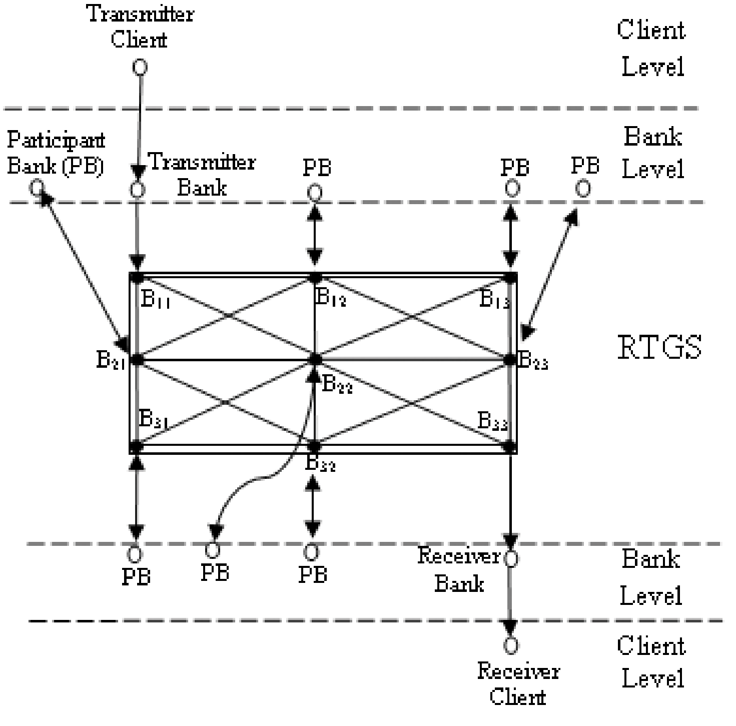

Figure 2. RTGS model using clearing house.

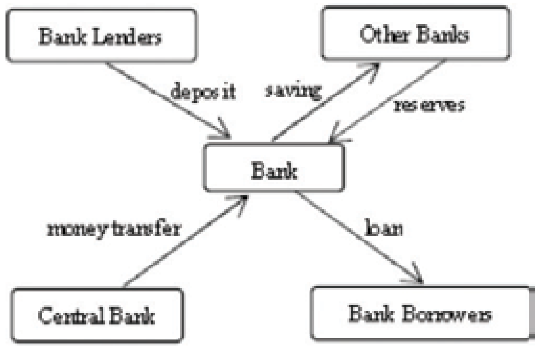

Figure 3. The adaptive agent.

Generally, the settlement process is influenced by the balance of the bank account that will carry out the settlement process in the central bank. The value of sufficiency in this discussion is influenced by the fulfillment of another bank participating in the clearing house. The fulfillment decisions made by other banks depend on the information provided by the agent in the clearing house.

The model used in this experiment is a decentralization paradigm that modeled network system's activity. The main component of this network is an adaptive agent consisting of five agents that are saving agent, reserves agent, loan agent, deposit agent, and money transfer agent, as shown in **Figure 3**.

The saving agents are in charge of finding and distributing the information needed in order to make the decision to save to another bank based on the health analysis of both banks so as to get the optimal profit. Reserves agents are tasked to find and share information related to the decision to take the reserve money in other banks based on the health analysis of two banks in order to obtain optimal benefits. Loan agents are responsible for finding and sharing information related to the profits to lend money to other banks based on the health analysis of two banks. Money transfer agents are given information concerning advantage that applies the deposit in central bank. Deposit agents have the duty to seek and share information about the profits when borrowing money from other banks based on the health analysis of two banks.

3.2. The agent-based model for SCM agribusiness

Supply chain management (SCM) philosophically is a chain that connects between companies, suppliers and customers. In the supply chain, a company connects between supplier to its upstream and distributor to downstream serving its customers. In general, the flow of material leads to the front while information and money flows backward in the established supply chain as shown in **Figure 4**. The purpose of supply chain management is to optimize services to customers at the lowest possible cost.

A 'value' can be created by the organization for itself and its customers. The creation of value can be done by participating in value chain activities. The value created by growing relationships

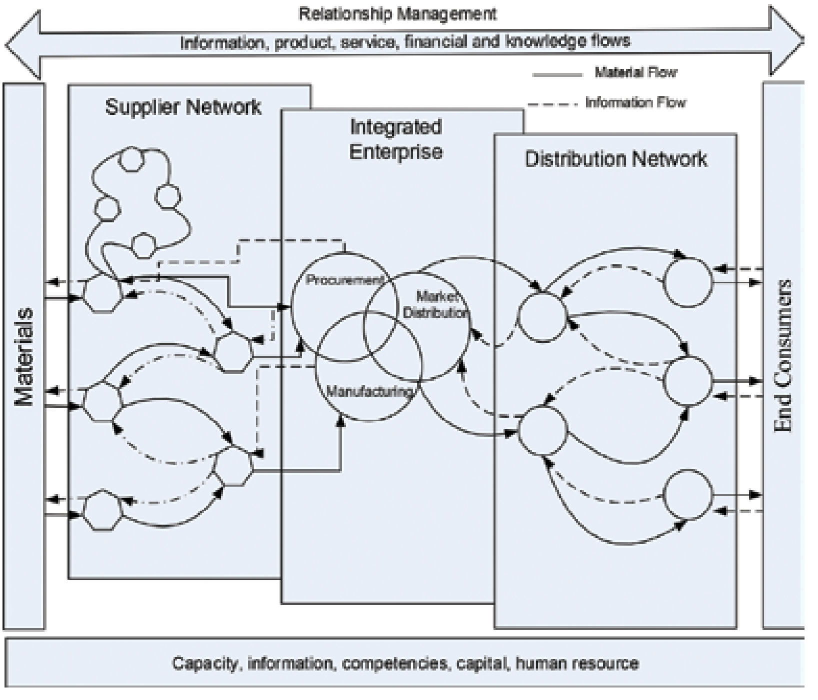

Figure 4. The networks model of modern enterprises.

is key in the supply chain. This key value is aggregated as the cumulative value of all exchanges that occur between the companies participating in the supply chain. The nature of the above agribusiness relationship highlights the traditional concept of the company. Traditionally, firms are perceived as separate and independent entities. When determining the chosen strategy, traditional companies seek to strengthen independence. This concept has been transformed into a network-based strategy. The contemporary concept assumes that the company is embedded in the network. The established network causes the merging companies to become interdependent. Because of interdependence, a strategic approach to relationship management in the network is required. The following diagram illustrates the nature of the relationships used by today's modern enterprises in the competitive environment among them in the network.

Figure 4 illustrates that firms need networking strategies to manage relationships with three different entity types around the supply chain environment, that is, (a) upstream with suppliers and downstream with customers, (b) horizontally with competitors and compliments, (c) with other key players in the economic, political/regulatory, technological and sociocultural environments [11], as shown in **Figure 5**.

On the basis of network strategy to manage relationships, this model created four agents that can manage the network. These agents are buyer's agent, competitor's agent, seller's agent and support's agent as shown in **Figure 6**.

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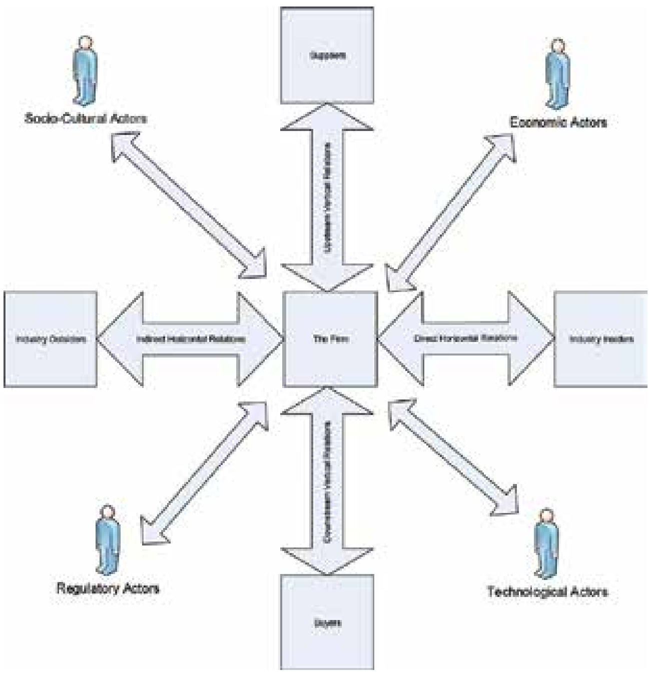

Figure 5. Network strategies to manage relationships.

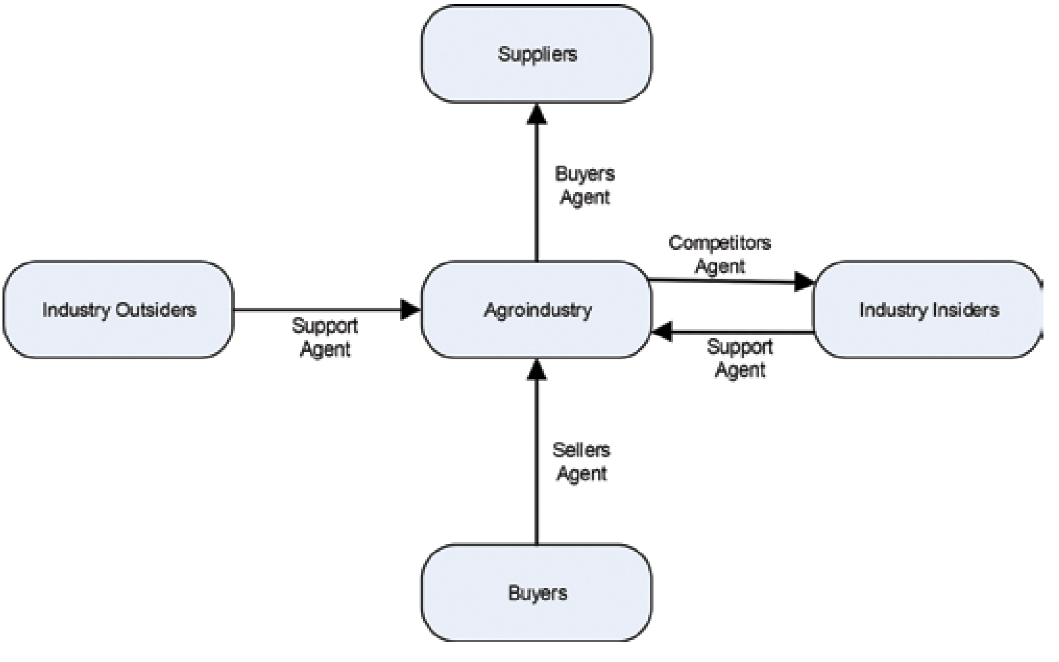

Figure 6. Network strategy based on four-agent information.

4. Forest fire model

This model starts with uncontrolled tree growth. After some time, lightning strikes will start fire. The fire will spread, destroying trees in large patches. Simultaneously, in the event of a fire, new trees will grow up again. If we have a probability of growth p and a fire probability q set at appropriate levels, we can see a growing group of trees and a burning group of trees, otherwise we just get a random distribution of empty, tree, and burning cells.

Forest fire model is the probabilistic cellular automata forest fire models follow the rules imitated from the phenomenon of forest fires and their growth. The rules built on probabilistic cellular automata forest fire models are as follows [12]:

1. A burning tree causes the area to become empty.
2. A tree becomes a burning tree if at least one of its nearest neighbors is on fire.
3. In the blank area, a tree grows with probability p.
4. A tree with the nearest non-burning neighbors becomes a burning tree with probability f.

4.1. Implementation forest fire model in serious game real time gross settlement (RTGS)

This model adopts the decentralization paradigm for modeling activity network system. The principal component of this system are adaptive agents consisting of five agents that are saving agent, reserves agent, loan agent, deposit agent and money transfer agent. Saving agents are in charge of finding and distributing the information needed in order to make the decision to save to another bank based on the health analysis of both banks so as to get the optimal profit. Reserves agents are tasked to find and share information related to the decision to take the reserve money in other banks based on the health analysis of two banks in order to obtain optimal benefits. Loan agents are responsible for finding and sharing information related to the profits to lend money to other banks based on the health analysis of two banks. Money transfer agents give information concerning advantage that applies the deposit in central bank. Deposit agents have the duty to seek and share information about the profits when borrowing money from other banks based on the health analysis of two banks.

Based on information obtained from these five agents, the decision impacts the value of net worth (NW): increased, decreased or permanent (does not form networks). The NW of a bank if it does not declare bankruptcy is the value of its assets (A), initial reserve holding (M) and payment due from other banks (DF) minus its liabilities initial level of deposits (C) and payment due to other banks (DT) as shown in Eq. (1) [13].

$$NW = A + DF + M - C - DT \tag{1}$$

Note that NW at time zero is $NW0 = A - C$, which we assume to be positive. If a bank declares bankruptcy, its net worth is given by α times its assets, minus α times its deposit liabilities, minus β times its interbank liabilities or net due $ND = DT - DF$ as shown in Eq. (2) [13].

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$$NW = \alpha(\text{asset}) - \alpha(\text{deposit}) - \beta(\text{net due} - \text{tos}) \tag{2}$$

$$NW = \alpha(A - C) - \beta(ND) \tag{3}$$

α and β values are in range $1 > \alpha > \beta > 0$. In other words, the cost of bankruptcy procedures reduces the value of bank's assets, but the bank also transfers the priorities of other banks participating in the payment network. Based on this assumption, bankruptcy punishes the holders of interbank claims disproportionately, implying that bankruptcy occurs in banks with large net debt positions compared to the capital they have.

In the RTGS system, the net worth of the bank at any point during the day is the difference between the original net worth and the value of liquidity penalty paid for the reserves throughout the day. Recall that the amount of reserves purchased at time t is given by L(t). Thus, the total liquidation paid at time t is given as shown in Eq. (4):

$$\pi(t) = \alpha \max L(t) – A1 \tag{4}$$

A1 is the asset value held as a bond. Based on this equation, if the liquidation of assets exceeds the value of A1, then the loan must be liquidated by reducing the loss and net worth of the bank. The NW at time t is shown in Eq. (5):

$$NW(t) = A - C - \pi(t) \tag{5}$$

Bankruptcy occurs when NW(t) moves toward a value of zero, this bankrupt condition can be modeled in the form of a mathematical equation like in Eq. (6) [13].

$$L(t) = L^* = \lambda - 1\ (A–C) + A1 \tag{6}$$

NW(t) is assumed to be impossible not to increase. With this assumption, it is unlikely that a bank with a zero net worth can be bailed out of bankruptcy. If the asset value is considered stochastic, then the analysis made will be more complicated as it should proceed with the values of the options it has.

At an early stage or at each step, the participant bank (the cell as shown in **Figure 7**) has a certain NW value. Banks that will carry out the settlement process, forming a network with other neighboring banks to meet the settlement process with forest fire model [14] as shown in **Figures 8–11**.

Figure 7 shows the starting position with eight banks that will perform the settlement process with positions at (x, y) = (1, 7), (2, 7), (3, 7), (4, 7), (5, 7), (6, 7), (7, 7), (8, 7), and (6, 5). The next step is viewed from one bank with position (6, 5), as shown in **Figure 8**.

Figure 8 shows the second step of the bank performing the settlement process with the position (6, 5) distributing the energy (funds) to the neighbor bank in positions (5, 4), (5, 5), (5, 6), (6, 4), (6, 6), (7, 4), (7, 5), (7, 6). Step 3 is shown in **Figure 9**.

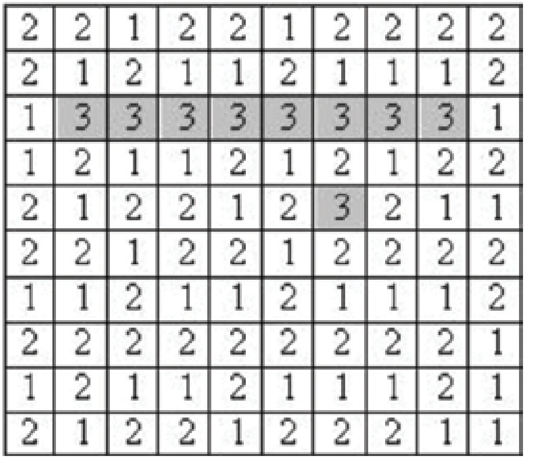

Figure 7. Settlement process using forest fire model in 1st step.

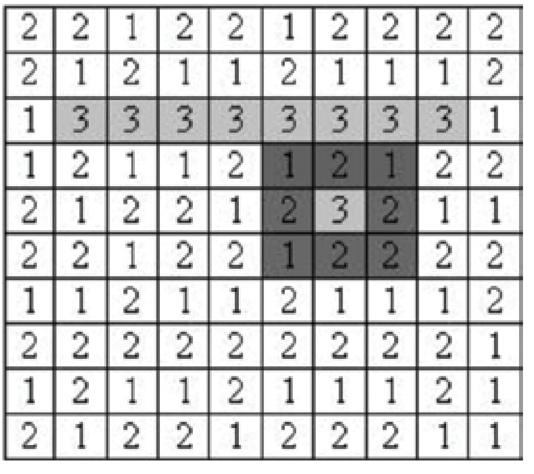

Figure 8. Settlement process using forest fire model in second step.

Figure 9 shows the third step of the settlement-holding bank with position (6, 5) proceeding to distribute energy (funds) to the second tier bank level (4, 3), (4, 4), (4, 5), (4, 6), (5, 3), (6, 3), (7, 3), (8, 3), (8, 4), (8, 5), and (8, 6). The energy distribution (funds) should also be in the banks with positions (4, 7), (5, 7), (6, 7), (7, 7), and (8, 7), but banks with those positions while doing the settlement.

Figure 10 shows the fourth step of a bank that performs a settlement process with position (6, 5) proceeding to distribute energy (funds) to third tier bank level with position (3, 2), (3, 3), (3, 4) (3, 5), (3, 6), (4, 2), (5, 2), (6, 2), (7, 2), (8, 2), (9, 2), (9, 3), (9, 4), (9, 5), (9, 6), and (9, 7). The distribution of energy (funds) cannot pass through the banks with positions (3, 7), (4, 7), (5, 7), (6, 7), (7, 7), and (8, 7) settlement. Step 5 is shown in **Figure 11**.

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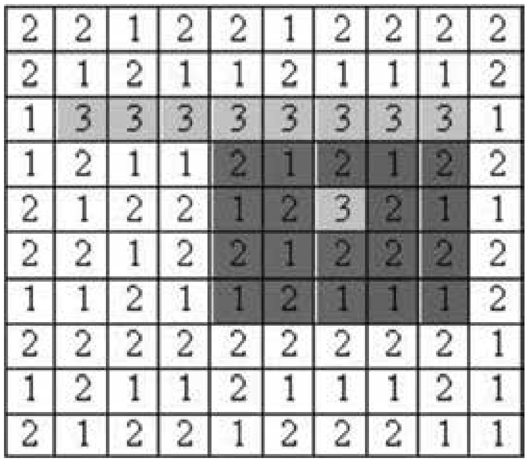

Figure 9. Settlement process using forest fire model in third step.

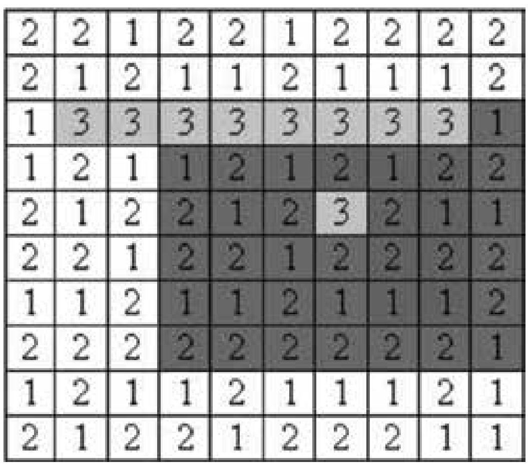

Figure 10. Settlement process using forest fire model in fourth step.

Figure 11 shows the fifth step of the bank performing the settlement process with position (6, 5) proceeding to distribute energy (funds) to the fourth tier bank position (2, 1), (2, 2), (2, 3), (2, 4), (2, 5), (2, 6), (3, 1), (4, 1), (5, 1), (6, 1), (7, 1), (8, 1), (9, 1), and (9, 8). The energy distribution (fund) cannot pass the bank in positions (2, 7), (3, 7), (4, 7), (5, 7), (6, 7), (7, 7), and (8, 7) who is doing the settlement process.

4.2. Implementation forest fire model in serious game supply chain management agroindustry

The physical environment of cellular automata (CA) is the universe of the CA that is computed. The physical environment of CA consists of a discrete lattice of cells. In this part, the physical environment of CA represents the part of supply chain management system that

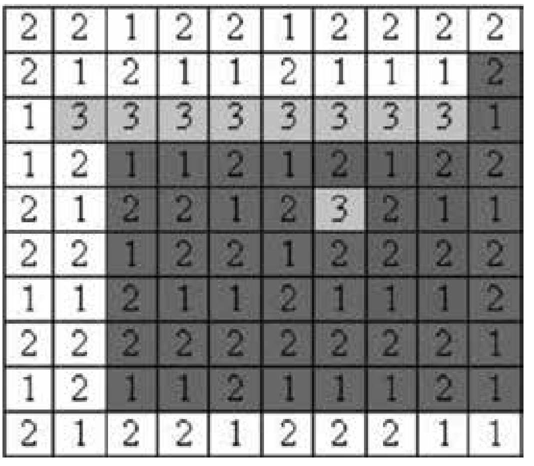

Figure 11. Settlement process using forest fire model in fifth step.

manages the buying and selling of tobacco between farmers and cigarette factory. The cells represent the cigarette factory that requires tobacco for the production process. Each cell can be in certain circumstances, and these cells represent the state of cigarette factory conditions. The position of the cigarette factory has four possibilities, namely: a potential to buy, a potential to not buy, position being bought, and positions have been bought.

For each cell representing the tobacco companies, the environment that consists of several tobacco companies that locally determine the evolution of the cell influences the SCM system. Environment consists of the cell itself plus the adjacent cell. In CA cell, there are some cells, for example, with a radius of 1; in addition to the cell itself, there are four cells again located on north, east, south, and west adjacent cells (von Neumann neighborhood), or the previous five cells as well as the four north-east, south-east, south-west, and north-west diagonal cells.

The rule of stochastic CA model acts on tobacco companies and their immediate neighborhood so that the cell's state changes from one discrete time step to another (i.e., system iteration). CA evolves in space and time as the rules are then applied to all cells in parallel. The evolution of CA regulations can use a deterministic or stochastic model. In this model, using the stochastic evolution model of CA because the next step is not only determined by neighboring cells but also by the results of previous processes.

The state of a cell (i, j) at the time t, can assume four values: (0) represents the "potential to buy", (1) represents the "potential for not buy", (2) represents the "being bought", (3) represents the "have been bought" [15]. The transition rules are:

$$\begin{aligned} &\textit{if } Nb < 1, \textit{then} < n\ (0) \rightarrow (0) \\ &\textit{if } Nb \geq 1 \\ &\textit{Then} \quad (0) \rightarrow (2) \text{ with probability p} \\ &(1) \rightarrow (1) \\ &(2) \rightarrow (3) \text{ after a time step} \\ &(3) \rightarrow (3) \end{aligned} \tag{7}$$

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0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	2	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	2	0	0
0	2	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	2	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Figure 12. Management of SCM using forest fire model in first step.

The result of the previous process is: Cigarette Factory (C1), position (3, 7), is “being bought.” This factory buys tobacco (T4) with NP 4.7. If there is excess tobacco, then it will be offered at the cigarette factory neighbors SCM members who require tobacco with similar qualities to profile rank 1 on its needs. Cigarette Factory (C2), position (7, 5), is “being bought.” This factory buys tobacco (T3) with NP 4.9. If there is excess tobacco, then it will be offered at the cigarette factory neighbors SCM members who require tobacco with similar qualities to profile rank 1 on its needs. Cigarette Factory (C3), position (1, 4), is “being bought.” This factory buys tobacco (T2) with NP 4.6. If there is excess tobacco, then it will be offered at the cigarette factory neighbors SCM members who require tobacco with similar qualities to profile rank 1 on its needs. Cigarette Factory (C4), position (4, 2), is “being bought.” This factory buys tobacco (T9) with NP 4.75. If there is excess tobacco, then it will be offered at the cigarette factory neighbors SCM members who require tobacco with similar qualities to profile rank 1 on its needs. The Cigarette Factories (C1, C2, C3 and C4) are shown in **Figure 12**.

Figure 13 shows the second step. The cigarette factories (position (3, 7), (7, 5), (1, 4) and (4, 2)) who make purchases distribute energy (tobacco farmers) to the cigarette industry neighbors. Cigarette factory (position (3, 7)) distributes to the cigarette factory with the position (2, 6), (2, 7), (2, 8), (3, 6), (3, 8), (4, 6), (4, 7), (4, 8). Cigarette factory (position (7, 5)) distributes to the cigarette factories that position (6, 4), (6, 5), (6, 6), (7, 4), (7, 6), (8, 4), (8, 5), (8, 6). Cigarette factory (position (1, 4)) distributes to the cigarette factories that position (0, 3), (0, 4), (0, 5), (1, 3), (1, 5), (2, 3), (2, 4) and (2, 5). Cigarette factory (position (4, 2)) distributes to the cigarette factories that position (3, 1), (3, 2), (3, 3), (4, 1), (4, 3), (5, 1), (5, 2), (5, 3).

Step 3 starts going competition between tobacco farmers to offer their crops at a cigarette factory that has not made a purchase. In case it is considered that the price of fresh tobacco in accordance with the hierarchy of tobacco companies obtain tobacco first so C1, C2, C3, and C4 so the market that occurred in SCM as shown in **Figure 14** as well as for competition that occurs in the fourth phase as shown in **Figure 15**.

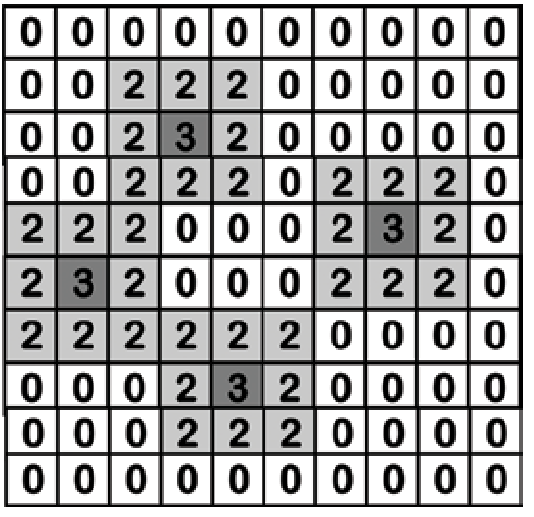

Figure 13. Management of SCM using forest fire model in second step.

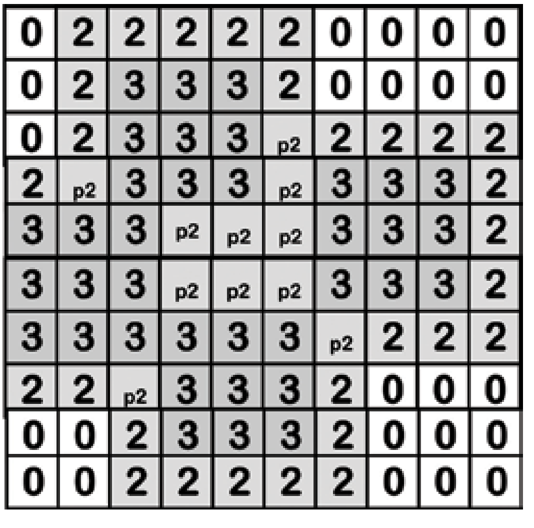

Figure 14. Management of SCM using forest fire model in third step.

Stock condition that simulated using serious game SCM using concept as discussed above can be shown as in **Figure 5**. Stock condition in **Figure 5** shows that the supply of tobacco from tobacco farmers to cigarette factories C1, C2 and C3 in stages.

4.3. The result of forest fire model in serious game real time gross settlement (RTGS)

Cells in this model represent banks that can be in three positions: (1) not forming a network for the settlement process that causes the net worth value does not change; (2) the value of net worth is decrease that influenced by saving agent and loan agent greater than other agent; (3)

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2	3	3	3	3	3	2	0	0	0
p2	3	3	3	3	3	p2	2	2	2
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	p2	2	2
2	p2	3	3	3	3	3	2	0	0
0	2	3	3	3	3	3	2	0	0

Figure 15. Management of SCM using forest fire model in fourth step.

the value of net worth is increase that influenced if deposit agent and reverse agent. Banks will only be in position 2 for one time round, after being in position 2 they will only be in position 3. Bank in position 3 cannot return. Each round consists of a bank analysis at position 2 to see if the bank will relate to its neighbors. The systematic way to analyze the cell will begin at the peak and then the process goes again clockwise around, the tested cell once again randomly generated to run the model with the specified probability.

Behavior of agents with varying probability values indicates that agent that affects net worth increases, agent that affects net worth decreases and the agent not form a network with probability 0.1 in the same time has a range of 90% as shown in **Figure 16**.

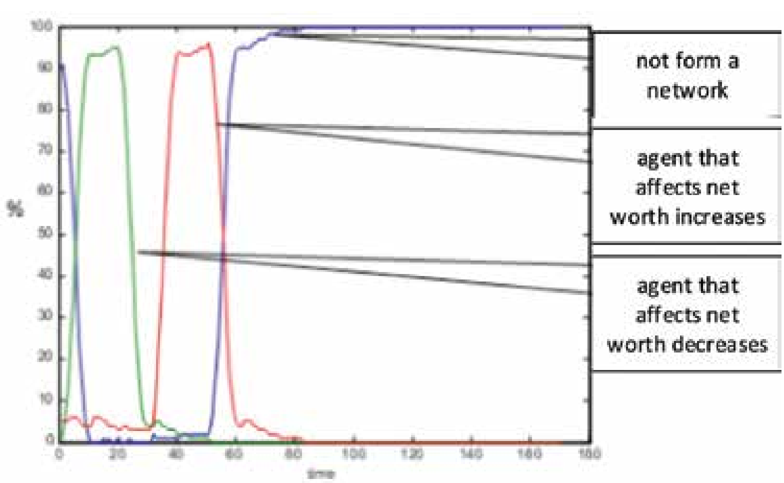

Figure 16. Behavior of agent with probability 0.1.

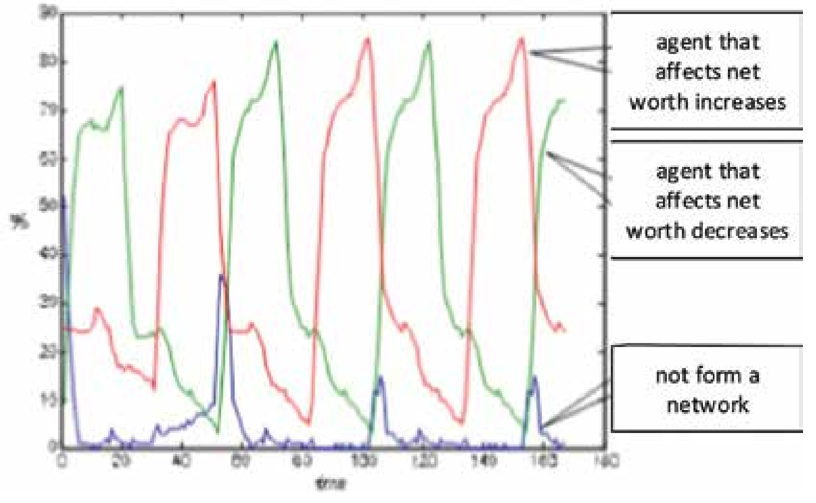

Figure 17. Behavior of agent with probability 0.5.

Agents that affect to increase the value of net worth and agents that affect to decrease the value of net worth with a probability 0.5 in the same time have a range of 60%. Agents that influence does not form networks with agents that affect to increase net worth and agents that affect to decrease net worth with a probability of 0.5 in the same time have a 35% range as shown in **Figure 17**.

Agents that affect to increase the value of net worth and agents that affect to decrease the value of net worth with a probability 0.7 in the same time have a range of 35%. Agents that influence does not form networks with agents that affect to increase net worth and agents that affect to decrease net worth with a probability of 0.7 in the same time have a 15% range as shown in **Figure 18**.

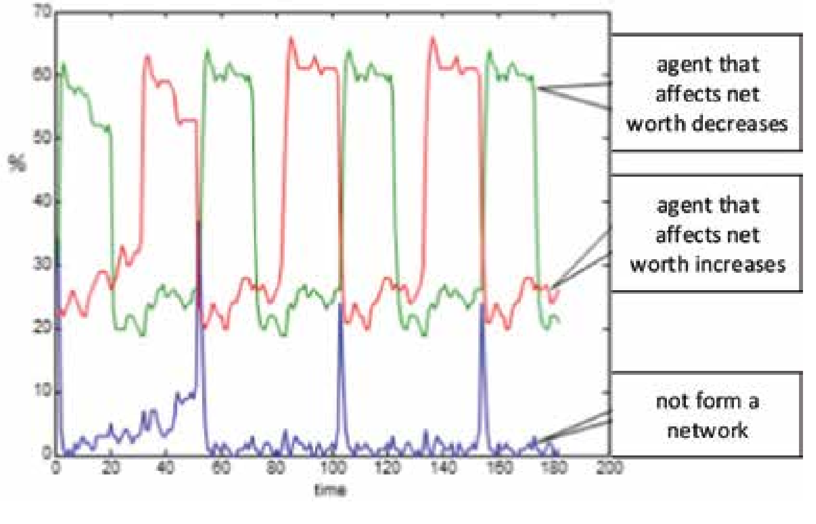

Figure 18. Behavior of agent with probability 0.7.

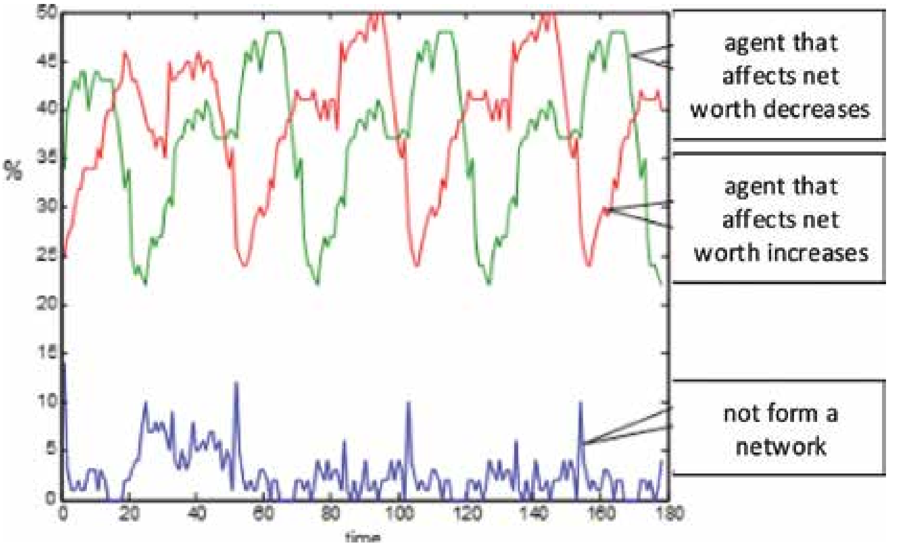

Figure 19. Behavior of agent with probability 0.9.

Agents that affect to increase the value of net worth and agents that affect to decrease the value of net worth with a probability of 0.9 in the same time have a range of 15%. Agents that influence does not form networks with agents that affect to increase net worth and agents that affect to decrease net worth with a probability of 0.9 in the same time have a 15% range as shown in **Figure 19**.

The flow of funds to the RTGS, particularly in the clearing house using the forest fire model, with a probability of 0.7 is shown in **Figure 20**.

Figure 21 shows that using probability 0.7, the flow of funds ends at step t to 150 to keep the net worth value in the RTGS at a stable value.

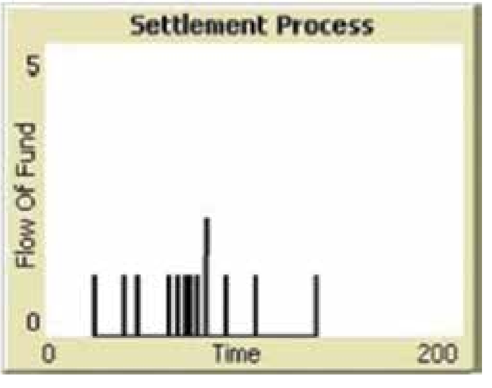

Figure 20. The flow of funds in the settlement process.

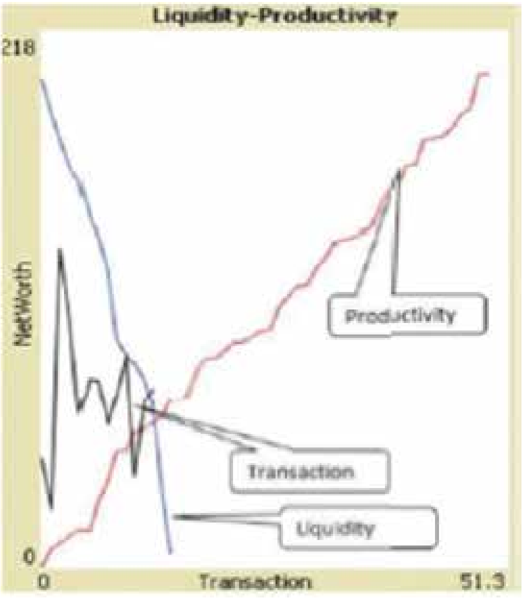

Figure 21. Efficiency in liquidity and productivity.

The efficiency of liquidity and productivity by using probability 0.7 with 15 banks transaction is shown in **Figure 21**.

4.4. Result of forest fire model in serious game supply chain management agroindustry

The intercompany network on supply chain management can be categorized as follows: (1) mutual independence, (2) unbalanced independence, (3) mutual dependence and (4) unbalanced dependence. The four networks formed are influenced by the capacity of companies that make up their networks and environments based on relational analysis of vertical, horizontal and other relationships as shown in **Figure 22**.

Figure 22 shows that each condition requires different handling and strategies. In conditions with mutual dependence, categories requires a strategic approach by network management to maintain network balance. In conditions with the category of mutual independence, it is necessary to maintain a degree of independence rather than maintain network integrity. In conditions with the category of unbalanced dependence required a strategy approach to manage networks that can create balance. Conditions with the category of unbalanced independence need a strategy to strengthen the company's independence.

Figure 22 shows that each condition requires different handling and strategies. In conditions with mutual dependence categories requires a strategic approach by network management to maintain network balance. In conditions with the category of mutual independence, it is necessary to maintain a degree of independence rather than maintaining network integrity.

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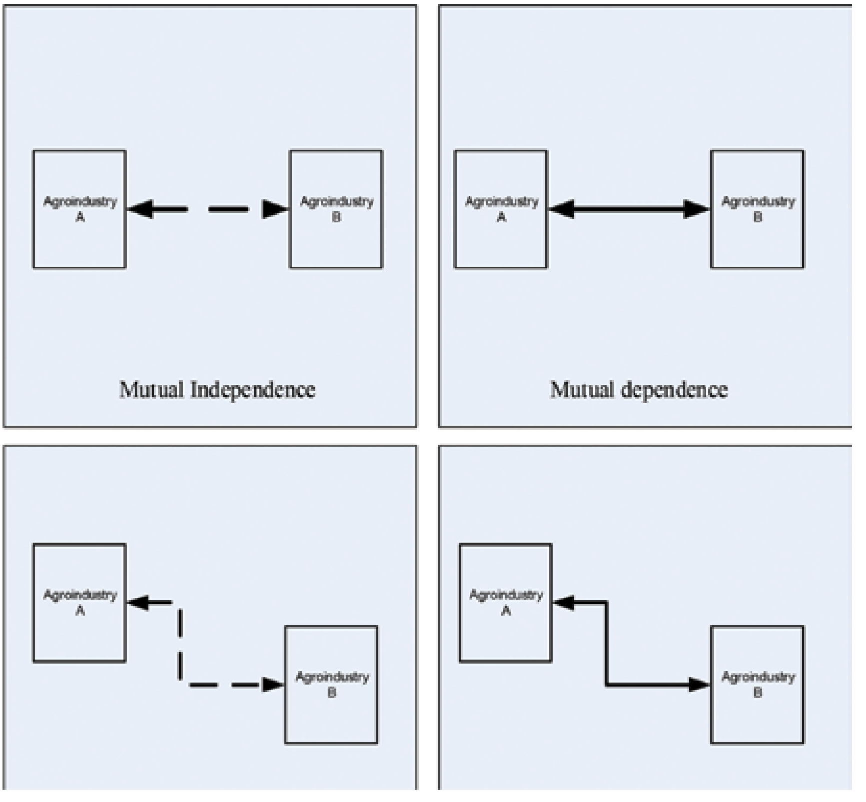

Figure 22. The probability of intercorporate network.

Figure 22 shows that each condition requires different handling and strategies. In conditions with mutual dependence categories requires a strategic approach by network management to maintain network balance. In conditions with the category of mutual independence, it is necessary to maintain a degree of independence rather than maintain network integrity. In conditions with the category of unbalanced dependence required a strategy approach to manage networks that can create balance. Conditions with the category of unbalanced independence need a strategy to strengthen the company's independence. The four categories of networks between agribusiness management (mutual independence, unbalanced independence, mutual dependence, and unbalanced dependence) can be detected by using a serious game agribusiness management by first modeling agribusiness network management and modeling data related to the agribusiness network as in **Figure 23**.

The result of modeling in the form of a serious game shows that the condition of the interdependence represented by x values starts with drastic degradation from the initial value close to a stable value that is in the range of value 0. This change of data gives an overview to agribusiness management to perform a strategy that can depress the network be balanced.

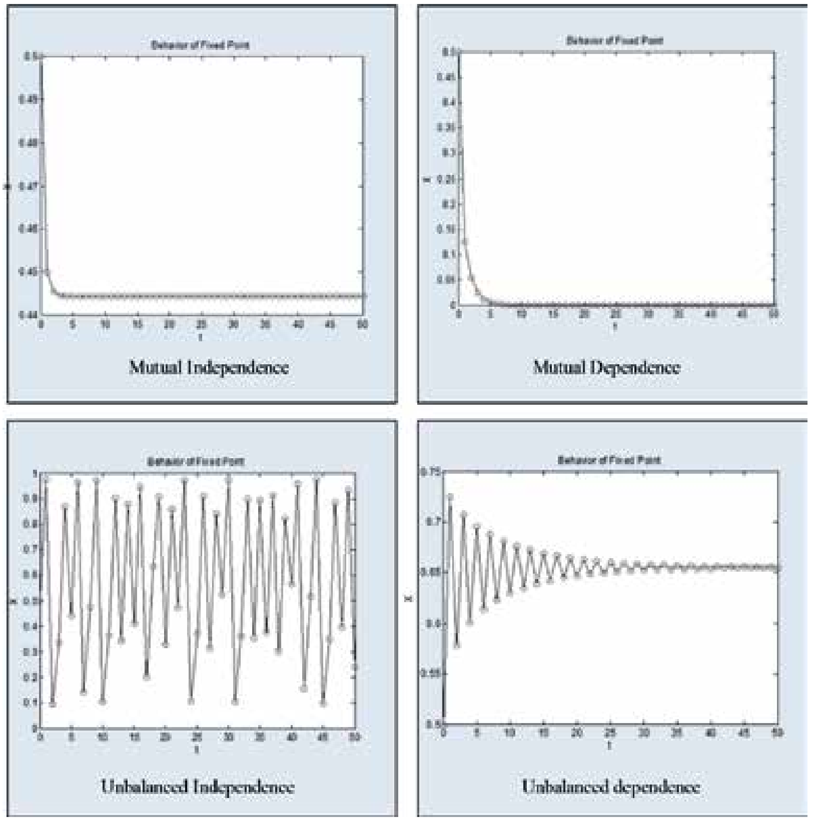

Figure 23. The fourth condition of intercorporate network.

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Chapter 5

Forest Fire Occurrence and Modeling in Southeastern Australia

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Christina Magill, Kerrie Tomkins and Warwick Hehir

Additional information is available at the end of the chapter

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Abstract

Forest fire is one of the major environmental disturbances for the Australian continent. Identification of occurrence patterns of large fires, fire mapping, determination of fire spreading mechanisms, and fire effect modeling are some of the best measures to plan and mitigate fire effects. This chapter describes fire occurrence in New South Wales (Australia), the Australian National Bushfire Model Project (ANBMP), fire propagation modeling methods, the McArthur's model and current forest fire modeling approaches in the state of New South Wales of Australia. Among the established fire models, PHOENIX Rapidfire predicts fire spread and facilitates loss and damage assessments as the model considers many environmental and social variables. Two fire spread models, SPARK and Amicus, have been developed and facilitated fire spread mapping and modeling in Australia.

Keywords: fire modeling, fire occurrence, PHOENIX Rapidfire, simulation, SPARK

1. Introduction

Forest fire is a ponderous and major threat with negative impacts sometimes lasting more than 10 years from the combustion period [1]. The degree of environmental damage due to forest fires is related to many environmental factors including topography, climatic factors, and vegetation types [2]. Topographic factors, ignition points, fire weather conditions, and fuel characteristics are contributing factors to the intensity and magnitude of fires [3, 4].

The vegetation in Australia is influenced and shaped by forest fires, due to the diverse varieties of floral composition, undulated terrain and a varied climate pattern, the vegetation in Australia [5]. The northern part of Australia represents tropical and subtropical climates and the south and south-east have temperate wet and seasonally dry climatic characteristics. The south-western part has a Mediterranean type climate and the central part of the continent is mainly arid and mainly free from large fires due to limited vegetation coverage [6]. The vegetation communities of Australia are largely fire adapted and dependent on fire for regeneration. In particular, the abundant Eucalyptus forests of Australia have high fuel loads, create large amounts of litter, and have higher volatile oil contents in leaves [7]. These forests are highly inflammable and more frequent to fires. Higher temperature, gusty wind, and scarce rainfall create the extreme fire weather condition which instigates big fires in the southeastern regions of Australia. New South Wales including the Australian Capital Territory (ACT) and Victoria and Tasmania are notable forest fire affected areas in the world [6, 8].

The temperate and tropical regions of Australia are affected differently by their weather systems. The southern part of Australia has a higher fire danger during the hot and dry summer months, whereas northern Australia has a higher fire risk during winter [9]. On average, Australia's worst forest fires occur in late summer and early autumn; although this does not specify that they cannot happen at any time or at a certain time of the year [10]. One of the worst events in world fire history is the Black Saturday Bushfire (7 February–14 March, 2009), which burned across Australia's Victoria State. If rain increases vegetation growth in the preceding winter, then the following summer season therefore has a higher fire danger. Topography, vegetation and climatic conditions play significant roles in fire spreading and in short- and long-term fire effects in southeastern Australia (**Table 1**).

Fires instigated in remote forest areas are difficult to manage and generally result in more environmental damages. People living close to fire-prone areas are much more vulnerable to loss of property and their lives due to fire [11]. The forest fire hazard in Australia results from the complex interaction of highly disparate natural and anthropogenic drivers. Natural variables include the type, as well as the amount, of living or dead plant substance, and the weather conditions that ordain the flammability and combustibility of vegetation.

The spread of fire relies mainly on topography and weather conditions though other associated factors (e.g., fuel type, fuel moisture content, and fire ignition) are also driving factors [12]. Rainfall and temperature regulate the short- and long-term fuel moisture content and fuel availability, which have significant impacts on fire occurrence [13]. Clarke derived trends in the Forest Fire Danger Index (FFDI) examining historical records of fire. There were 38 weather stations that recorded forest fire from 1973 to 2010 and no decreasing trend of forest fire events was found in NSW [10]. Fires have different characteristics based on existing vegetation types, fuel loads, and combustibility [14]. Consequently, fire danger prediction relies on vegetation types and climate conditions [15]. Topographic factors and vegetation influence weather patterns, creating microclimates for fire ignition, occurrence, and spread. Apart from environmental factors, human activities at the wildland-urban interface can impact fire occurrence and can increase fire danger [16–18].

Fire event (name)	Area burned (ha)	Date
Southern Highlands bushfires	250,000	5–14 Mar, 1965
1980 Waterfall bushfire	>1,000,000	3 Nov, 1980
1979 Sydney bushfires	>1,000,000	24 Dec, 1979
1994 Eastern seaboard fires	~400,000	27 Dec, 1993–16 Jan, 1994
Lithgow bushfire	400,000	2 Dec, 1997
Black Christmas	300,000	25 Dec, 2001–7 Jan, 2002
2006 Central Coast bushfire	160,000	1 Jan, 2006
Jail Break Inn fire	30,000	1 Jan, 2006
Pulletop bushfire	9000	6 Feb, 2006
Warrumbungle bushfire	54,000	18 Jan, 2013
2013 New South Wales bushfires	100,000+	17–28 Oct, 2013

Reference: https://www.canyonleigh.rfsa.org.au/australian-bush-fire-history; http://edition.cnn.com/WORLD/9712/04/australia.fires/; http://royalcommission.vic.gov.au/Finaldocuments/volume-1/HR/VBRC_Vol1_AppendixB_HR.pdf (Accessed on 19 February, 2018).

Table 1. Large fire events and burned areas (in hectares), where known, in New South Wales, Australia.

Researchers have used empirical models [generalized linear model (GLM)] to assess the characteristics of fire occurrence [19]. In most Australian eco-regions, vegetation structure and composition vary spatially and vegetation formations regulate fire occurrence patterns. The aims of this chapter are to describe the big fire events and the major driving factors of fires in New South Wales, basics of forest fire modeling and previous and present fire models of New South Wales of southeastern Australia.

2. Fire in Eucalyptus forests of Australia

Fire is an integral part of the dry and wet Eucalyptus forests of Australia [20, 21]. Eucalyptus species in Australia are fire adapted and regeneration of eucalypt species also depends on fire [22]. Grasslands and sedge lands of the *Sclerophyll* forests are driving factors for fire intensity and propagation in these forests. The understory vegetation of the dry *Sclerophyll* forests plays key roles in fire frequency and intensity [22]. Wet *Sclerophyll* forests have lower fire dangers compared to dry forests. In Tasmania, changes in fire occurrence and burned areas have profound impacts on the composition and structure of the dry *Sclerophyll* forests [23]. Eucalypt species that grow in a severe fire climate can generally survive in a high-intensity fire. In the case of a young tree burned severely, the branches and stems die, but the tree can survive by producing several new stems from buds near ground level. Older trees survive through producing epicormic shoots from bud strands on the stem and larger branches. Dry *Sclerophyll* forests tend to be affected by a fire every 4 to 20 years.

3. Forest fire occurrence in southeastern Australia

Hilly areas, forests, savannas, and densely vegetated landscapes are more prone to forest fires than grasslands and shrublands; buildings and infrastructures in these areas are also at higher risk. Incorporating socioeconomic variables with environmental variables can bring about a more efficient management tool, incorporating fire occurrence prediction to assist management. To understand the spatial pattern of fire, it is necessary to understand the characteristics that control the area burned, e.g., vegetation growth, dry fuel abundance, fire weather, and ignition; unavailability of any of these factors can limit the area burned. In Penman et al., spatial ignition patterns of *Sclerophyll* forests in the Sydney basin were compared with northern hemisphere coniferous forests [17]. Patterns of lightning ignition and arson procured were very similar to the results obtained from the North American coniferous forests and other ecosystems. Speculation based on the Sydney area of southeastern Australia showed that while fires ignited by arson tended to occur at ridges near anthropogenic infrastructures, fires ignited by lightning tended to start at ridges further from infrastructure. The results also showed that fires ignited by lightning tended to occur in fuel older than 25 years, while fires from arson tended to occur in fuel younger than 10 years. It was suggested that since arson ignitions occur at shorter distances to urbanized regions, these fires pose higher threats to highly valued resources and assets (HVRA) compared to fires from lightning; therefore, forest managers should prioritize and emphasize management of arson ignitions since the goal is to constrict the social and economic loss [17].

4. Australian national bushfire model project

The first personal computer-based bushfire model, Australian national bushfire model (ANBM), in Australia, was developed under the National Bushfire Research Unit in 1987. This real-time model was to facilitate decision-making in emergency condition and for the bushfire management. The inputs of the ANBM were fuel types and conditions, topographic factors, and economic modules. Rothermel and McArthur's fire model were embedded in the processing engine to delineate the fire spread and fire perimeter spatially. The model was the first initiative to integrate geographic information system (GIS) with real-time data. The outputs of the ANBM were graphical and were able to show fire front (using Huygens principle) at any desired scale. The ANBM was a successful first initiative and nowadays, many fire models have similar model architecture like ANBM, though the computational capabilities and input parameters have increased in the recent developed fire spreading models [24].

5. The McArthur Forest Fire Danger Index (FFDI)

McArthur's model, a tool to simulate complicated weather variables, is still being used all over Australia for fire danger rating and forecasting [26]. The first fire scientist of Australia,

Category	Forest	Grassland
Catastrophic	>100	>150
Extreme	75–99	100–149
Severe	50–75	50–99
Very high	25–49	25–49
High	12–24	12–24
Low moderate	0–11	0–11

Table 2. Australian fire danger rating for Australian forests and grasslands [25].

A. G. McArthur, developed this fire danger index and this fire danger index has been utilizing to disseminate fire danger information all over Australia. The McArthur FFDI includes rainfall, evaporation, wind speed, temperature, and humidity to describe the fire danger level of the fire-prone areas of Australian continent. The developed fire danger rating scale for forest and grassland are given in **Table 2**.

McArthur's fire danger scale and meters are significant achievements for forecasting fire and fire spread. The spatial distribution of FFDI was calculated for NSW using the McArthur's equation [26]. McArthur's meter was for the grasslands, known as McArthur's Mark 3 meter and McArthur's meter for forests (known as McArthur's Mark 5 meter) was developed especially for the Eucalyptus forests of Australia. These two models, Mark 3 and Mark 5, are commonly used for grassland and forest fire danger forecasting, respectively, today [27].

6. Forest fire modeling and simulation: concepts, types, and examples of models

Forest fire modeling is classified by the nature of underling equations into theoretical, empirical or semiempirical. Two types of forest fire models are being used: wildland fire spread and fire-front property models. According to physical systems, these models are divided into surface-fire models, crown fire models, and spotting and ground fire models. While theoretical models are based on fluid mechanics, heat transfer and combustion laws, empirical models rely on statistical correlations derived from previous studies of forest fires, and semiempirical models are theoretical models fused with statistics [28].

From the perspective of variables, wildland fire spread models give physical estimates of the fire perimeter and fire-front models illustrate the features of the fire geometrically. Furthermore, when divided based on physical systems—surface-fire models consider vegetation of the lowest strata, that is, less than two meter height, crown fire models consider surface and aerial strata of vegetation, spotting models consider fuel beyond the main fire area, and ground fire models consider the humus layer on the ground.

Theoretical surface-fire models incorporate fuel, terrain, and climatic parameters in a simplified way so that mass, momentum and energy-conduction, convection, and radiation-transfer can be quantified to describe fire propagation. Empirical surface-fire models, initially developed by McArthur, use statistical correlations from experimental fires. The aim of crown fire models is to analyze fire transition conditions from surface to crown, and to study behavior variables. Therefore, crown fire models are classified as initiation and spread models [28].

Modeling forest fires from a combination of mathematical equations allows descriptive predictions of the spatial and temporal evolution of fire behavior variables. Forest fire modeling is a multi-scale concept and integrating natural physical processes into the model environment is a challenging task. Simplification of physical processes reduces computation and output processing time. Large fires have multifarious impacts on nature and the human environment and are complex to simulate as complicated fire meteorology, spatial heterogeneity and complex fuel structure and availability are associated with fire propagation. Forest fire spread forecasting depends on accurate weather prediction, precise ground information about fuel types, conditions, and topographic factors. Any complexity and errors in predicting these factors can induce incorrect forest fire hazard prediction and forecasting [29].

6.1. Mathematical models

Mathematical modeling has been used to predict the fire propagation and fire effects. Mathematical models are important tools for predicting fire effects, fire suppression actions, and in strategic fire management and planning. Nowadays, mathematical models have been used to predict the vegetation response in fire severity forested areas and park managers are using mathematical modeling techniques for fire planning and management. The validated and experimented mathematical fire models are reducing uncertainty through providing robust assessment of fire propagation, fire effects, and in generating future fire regime scenarios. These modeling techniques are reducing the range of variables and facilitating data-processing through constructing empirical relationships [30]. Integration of fire intensity, flame height, and wind speed in a mathematical modeling framework is allowing fire researchers and scientists to predict the possible fire impacts on emergency and after-fire management [31].

6.2. Physically based forest fire simulation model

Physical fire models are utilized to understand the fire behavior and spread rate scenarios in heterogeneous landscapes. The modification of terrain and physical environmental parameters in a small scale provides realistic results to understand the fire spreading and behavior. Two-dimensional physical fire models are built based on energy conservation laws, heat transfer, and convection mechanism which are commonly used all around the world. Two-dimensional fire models integrate wind and slope effects under different fuel type conditions and provides actual understanding of the natural fire environment-climate interactions in a controlled environment [29]. Three-dimensional or complex physical fire models integrated with fluid dynamics concepts can help generating robust and factual experiments. NCAR's

Coupled Atmosphere-Wildland Fire-Environment (CAWFE) model [32], WRF-Fire model [29], FIRETEC model [33], and fire dynamics simulator [34] are the examples of physical fire models, which are being used to understand the fire behavior and propagation.

6.3. Data assimilation model

Data assimilation models use dynamic data-driven application system (DDDAS) techniques to simulate scenarios [35]. DDDAS toolbox is widely used to incorporate additional data to execute a model and can reverse the action of steering the measurement process. A fire combustion model is developed integrating single semi-empirical reaction rate in the assimilation model. In other words, reaction-convection-diffusion processes are integrated in the Arrhenius equation to understand the chemical reactions and to estimate the fire-front temperature. This fire combustion model can generate output scenarios for predicted combustion waves, fire-front temperature, and post-frontal burned area, predict combustion zone and can model fire propagation and direction [36].

6.4. Statistical fire models

Statistical methods have significant role in forest fire prediction. The statistical science can make significant contributions to improve the forest fire prediction in case of local to global scales. The integration of stochastic statistical estimation in fire phenomena can provide decision-making supports for better fire planning and management. Statistical predictive models have been used to model fire spreading, burned area estimation, and fire impacts. In a study [37] of forest fire modeling in southern Australia, logistic regression was used to integrate land cover, topographic data, vegetation indices, and socioeconomic variables along to delineate the spatial pattern of a forest fire on a grid of 1 km^2 over a period of 11 years. This study found that densely vegetated landscapes, mountainous regions, savannas, and forests are most prone to forest fires. Grasslands and shrublands are relatively less preferable zone for forest fires. Moreover, socioeconomic phenomena are useful in the overall results of the prediction and environmental factors play individually strong roles in the prediction of fires [37].

6.5. Empirical and simulation models

The quantitative estimation of the risk of damage of properties is necessary for the implementation of an evidence-based approach in case of the management of forest fire [17]. The empirical and simulated results of predicted fire spread and possible impacts on properties and natural environment are helpful in assessing wide range of risk-reduction techniques. Simulated weather warnings are the main drivers of forecasting fire danger index in Australia [38]. Advancements of the simulation modeling allowed us to quantify fire risk and have been widely used not only in Australia [39] but also in the USA [40] and Europe [41]. Fire empirical models are widely used in assessing likelihood of fire ignition [17], ignition, and spread distance of fires [42], fire risks, and prescribed burning planning [1, 43], and fire impacts in wildland-urban interfaces (WUI) [44]. In southern Australia, FIRESCAPE-ACT was used [45]. FIRESCAPE-SWTAZ is an updated version of the FIRESCAPE-ACT to forge fire rules for the heterogeneous landscapes in Tasmania, Australia [46]. A sophisticated state-and-transition model is embedded in the FIRESCAPE-ACT model for the heterogeneous landscapes [46].

In southeastern Australia, LAndscape MOdeling Shell (LAMOS) is used to emulate the progressive dry *Sclerophyll* forest [47]. LANDscape Succession Model (LANDSUM) is a spatially-explicit stochastic simulation model which has been used to understand fire occurrence and fire spreading at local and regional scale [48]. In [49], the researchers compared LANDSUM and other four landscape fire models in Australian continent. LANDSUM model has different purposes to use as a fire and forest management tool.

7. PHOENIX Rapidfire, SPARK, and AUSTRALIS model examples from Australia

Many fire models were analyzed already and still many are in ongoing process. Some statistical fire models in Australia are developed using the binomial (logistic) regression. Binomial regression techniques are used to model the fire behavior in relation to distance, weather, fuel types and conditions, and fire barriers [50]. Fire weather has significant roles in defining fire regimes of southeastern Australia and the associated fire weather parameters are critical to integrate and model in the real-time or empirical modeling framework. In [50], researchers integrated fire weather parameters, fuel treatment, and terrain factors to predict the fire risk in Greater Sydney using logistic regression and achieved 98% predictive accuracy in fire risk modeling which can be considered as a complement to simulation methods. Fire simulation modeling in southeastern Australia integrated fuel types, quantity and conditions, and topography to understand fire spreading and fire behavior [39, 51]. The fire behavior models in southeastern Australia are developed under a limited range of controlled considerations. Researchers found that fire behavior and propagation simulation results showed a moderate level of prediction accuracy comparing with the real fire scenarios [52–54].

Prediction methods based on formal bushfire behavior have been in development for nearly a century [55]. Most models here have focused on the deterministic prediction of the spread rate of the front of the fire as this is critical to the application and control of fire [56]. Physical and quasi-physical models were used to represent the chemistry and physics of fire spread, while statistical relationships between variables observed during field and laboratory experiment can be delineated using quasi-empirical and empirical models [56, 57]. Physical fire spread models are generally computationally heavy as these models are driven by environmental forces and are not operationally practical [56]. Empirical models utilize readily usable fuel and weather data as inputs and as they are generally relatively simple, analytical models that do not attempt to include any physical understanding of the combustion processes involved, can be solved relatively quickly [55].

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7.1. PHOENIX Rapidfire

Although there are numerous fire spread simulators, their scale is way larger than necessary for the highest loss risk zones, which are known as the wildland-urban interface, where the interaction between vegetation and humans happens. In Australia, PHOENIX Rapidfire (PHOENIX) is the fire simulator which has been modeled to illustrate fast spreading and large fires. PHOENIX combines firebrand transport and ignition's contribution to the spreading of the fire [58]. In [58], researchers used the illustrated example of the forest fire in Cavaillon, France, where spotting was a major trend and hot coal was flowing from high peaks and flown to adjacent channels to spread the fire. Afterward, to make the spotting pattern comparable to the ones in Cavaillon, the thresholds were recalibrated manually. For fires like the Cavaillon fire, where spotting is the key spreading mechanism, it is necessary to first simulate small-scale spotting. Moreover, the ember density modeling is useful in predicting the effects on HVRA; this can be auxiliary to other thresholds of standard intensity. Nevertheless, it was suggested to conduct further detailed testing of its use in other types of fire events before employing it widely. PHOENIX has the capacity to analyze the characteristics of fire spreads in the scale as small as WUI; this makes it a very useful tool in estimating the risk of impact, fire behavior reconstruction, vulnerability modeling, evaluation of fire management plan, and suppression process [58]. In [59], researchers derived simulated fire severity values using PHOENIX. PHOENIX Rapidfire was simulated to understand the fire extent and behavior of the Black Saturday fire [60].

7.2. SPARK model

SPARK is a fire spread simulation toolkit for Australia. SPARK uses set method which is directed by a user-defined algebraic spread rate for the fire propagation modeling [61]. Small-scale and complex bushfire scenario can be simulated within this modular-workflow based bushfire simulation package. SPARK allows user-defined spread models which makes SPARK a flexible modeling package which is free from complex-coded spread models.

The easy to implement user-defined models enables SPARK as a different spread modeling testing platform as well. The level set method of SPARK facilitates integrating fire perimeter and other environmental parameters to assess fire spreading. SPARK includes a workflow environment allowing faster processing and visualization using high-performance computation capabilities. A fire propagation module (spark propagation solver) can be run from the workflow environment. The model inputs are atmospheric parameters, fuel types and conditions, topographic factors, and fire ignition points. The input parameters are flexible and can be sourced from a range of databases based on the scenario. SPARK has many in-built operation packages and the output of the model is raster-based which can be modified and integrated with other social and environmental parameters in any remote sensing software or in GIS platforms. The final output shows the spreading over time which is important to predict and take necessary initiative for fire management.

7.3. AUSTRALIS simulator

AUSTRALIS is a high-performance forest fire simulator that allows the location of a forest fire to be rapidly predicted. A methodology used to evaluate the accuracy of forest fire simulators using historical fire data is presented and applied to the AUSTRALIS forest fire simulator using the four distinct phases of a large-scale forest fire occurring in Western Australian sand-plain heathlands. The AUSTRALIS forest fire simulator allows the future location of a forest fire to be rapidly predicted, and geographical information systems (GIS) maps with forecast fire-lines overlaid on them to be quickly made available to fire managers, the accuracy of such simulators needs to be examined by application to high-quality datasets from prior fires. AUSTRALIS employs a discrete event simulation technique that is based on partitioning the landscape into a collection of two-dimensional cells and calculating the propagation delay between an "ignited" cell and each of its "unburnt" neighbors. The discrete event simulation approach of AUSTRALIS relies on spatial discretization, where the landscape is partitioned into cells that are assumed to have homogeneous attributes, such as vegetation, slope, and aspect. Each cell contains state information ("unburnt" and "ignited") and many attributes relevant for calculating propagation delay, including location, elevation, and fuel characteristics such as vegetation type and fuel load. In contrast to other cell-based approaches to forest fire simulation, the cell locations are distributed randomly, rather than regularly, across the landscape [62].

8. Conclusion

There are many fire spread models in the different regions of Australia. In Western Australia, AUSTRALIS simulator is widely used for fire propagation mapping and modeling. The Commonwealth Scientific and Industrial Research Organization (CSIRO) has developed a new fire knowledge base platform (Amicus) for Australia and Amicus will be used as a complimentary knowledge base with the PHOENIX Rapidfire. SPARK is a new toolkit for fire spread prediction and modeling for Australia which is also developed by CSIRO. These established fire spread models have been utilized for better fire management planning and forest management.

Conflict of interest

The authors declare no conflict of interest.

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Section 3

Susceptibility and Recovery After Wildfires

Chapter 6

Post-Fire Vegetation Recovery in Iberia Based on Remote-Sensing Information

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Additional information is available at the end of the chapter

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Abstract

A previously developed procedure that aims at monitoring the process of vegetation recovery in areas affected by major fire episodes is revisited and assessed in terms of consistency and robustness. The procedure is based on 10-day fields of Maximum Value Composites of the Normalised Difference Vegetation Index (MVC-NDVI). The identification of fire scars is first achieved based on cluster analysis of persistent NDVI anomalies during the year following the fire event. Post-fire vegetation behaviour is then characterised based on maps of recovery rates as estimated by fitting a mono-parametric model of vegetation recovery to NDVI data over each burned scar. Results obtained indicate that reliable estimates of vegetation recovery times may be achieved using time series of NDVI of moderate length. It is also shown that consistent results are obtained when time series are derived either from 1-km spatial resolution data retrieved by the VEGETATION sensor on-board SPOT or from 250-m spatial resolution data from the MODIS instrument on-board Aqua and Terra. The regeneration model is also applied to estimate recovery rates in the case of recurrent fires. Overall results point out that the proposed methodology may play an important role in studying vegetation recovery and species succession after recurrent fires, namely when one vegetation type is replaced by another that regenerates faster, despite being more flammable and therefore increasing the risk of severe and large fires. The robustness of the proposed model highlights its adequacy to assess post-fire vegetation dynamics and therefore the procedure reveals as a promising tool for planning and implementing of better fire management practices before and after fire events.

Keywords: vegetation recovery, large fires, mono-parametric model, MODIS, NDVI

1. Introduction

Wildfires are a major disturbance striking most terrestrial ecosystems [1, 2], with important impacts on land degradation and desertification, vegetation composition, biomass loss [3, 4] and changing the hydro-ecological regimes [5, 6]. Forest fires induce soil impoverishment due to the loss of nutrients during and after the fire, by runoff. The erosion processes may be accelerated due to the loss of soil cover; a minimum of 30% in soil cover is required to protect the soil against erosion [7], and the time needed to reach this protection level influences the erosion risk.

In Mediterranean regions, fire is frequent and plays an important role in controlling the evolution of ecosystems [4]. Despite being mostly of anthropogenic origin, the influence of the expected rise of temperature and evapotranspiration in the near future will contribute to increasing the frequency and severity of wildfires in the region [8, 9]. Other factors related with land-use management, namely rural abandonment and replacement of crops by grassland, also contribute to increasing fire frequency [10]. Although some plant species are able to recover and regenerate by means of either resprouting [11, 12] or germination of fire-protected seeds, stored in the soil or in the canopy [13, 14], not all plant species survive forest fires. Therefore, vegetation density and composition of Mediterranean ecosystems should be affected by recurrent fires [8, 13]. The replacement of pre-fire forest areas by shrubland or grassland after recurrent wildfires is mainly associated with the elimination of species that take long recovery times, such as *Pinus halepensis* Mill., that require almost two decades to fully recover [15]. Días-Delgado et al. [8] found that areas dominated by *Quercus* spp. were more resilient than forests in Central Portugal, dominated by *Pinus* spp. The regeneration in forests dominated by *P. pinaster* in Portugal was slower than in an area mainly populated by Eucalyptus that may quickly re-sprout from buds after fire [16]. Nevertheless, small intervals between fire occurrences may lead to plant species not reaching reproductive maturity, as happened to *P. pinaster* populations in Portugal [17]. Results from Tessler et al. [18] indicate that forest recovery after recurrent fires is more related with time within fires than with the number of previous fires.

During the process of recovery, vegetation may also be influenced by several environmental factors, such as fire severity/damage and climatological extreme events. Vegetation recovery depends on several climate factors, such as the occurrence of droughts, which may inhibit vegetation growth, but also on precipitation of high intensity, which contributes to nutrient loss and erosion by runoff [19]. In Portugal, fire damage has been identified as a main driving factor of vegetation recovery [20], but drought episodes occurring in post-fire conditions have also been shown to delay recovery times for several months [21].

Forest fires are recurrent in Portugal where the flammable material is high, and the moisture content is low, either due to climate conditions, to land-use change, or to a combination of the two. Wet and mild winters, together with dry and warm summers, favour the growth of the vegetation and its subsequent low moisture content, due to water stress [4], whereas the replacement of agricultural land by forest plantations or shrubland increases the available fuel [13, 22]. Large fires are promoted by the occurrence of high temperatures and drought episodes [23] that may lead to total burnt areas several times larger than the average, such as the burnt areas in 2003 and 2005, with amounts of 425,000 and 339,000 ha, respectively, that were until this year record breakings in the national history of fire events [24]. The fire season of 2017 in Portugal has been catastrophic by most accounts. The authorities reported more than 100 human fatalities, with about 500,000 ha of estimated burnt area which corresponds to the maximum record since 1980.

In the last decades, information from different sensors on-board several satellites has revealed to be a powerful tool to study and monitor vegetation dynamics, such as the influence of climate on vegetation [25, 26] including the effect of droughts [27, 28]. The Normalised Difference Vegetation Index (NDVI), as derived from SPOT-VEGETATION imagery, has been successfully used to identify large burnt areas in Portugal, given that burnt scars present very low values of NDVI anomalies following the fire [16].

Monitoring vegetation recovery is a very challenging and expensive task, and remote-sensing information has also been successfully used to monitor post-fire vegetation recovery [29–33]. Gouveia et al. [16] presented a procedure that allows monitoring the vegetation regeneration in the years following the 2003 fire season using 10-day fields of Maximum Value Composites of NDVI at 1-km x 1-km spatial resolution derived from the VEGETATION instrument. They selected two large burned scars located in Central and South-western Portugal and they showed that the post-fire vegetation dynamics in those areas could be characterized by fitting a mono-parametric model of vegetation recovery to NDVI over each burned scar. The patterns of recovery time over the two regions highlighted the different regeneration processes of different forest types, the region located in Southwestern Portugal presenting a faster recovery, which could be associated with a dominance of Eucalyptus. However, the dataset from VEGETATION available at the time was restricted to 1998–2006, a period not long enough to allow assessing the accuracy of the model's estimates. Later, Bastos et al. [20] provided a preliminary assessment of the model accuracy by comparing the regeneration rates obtained by the application of the model described to the same two regions analysed in Gouveia et al. [16] but using both the original 8-year dataset (1998–2006) and an updated one, extended to 11 years (1998–2009). They also successfully applied the technique to seven other burned areas of fire seasons from 2003 to 2005.

NDVI has also been used to assess the impacts of drought conditions on vegetation recovery [20, 21]. For instance, the occurrence of a severe drought event in 2004–2005 led to a decrease in recovery rates in the case of the burned scars of the 2003 fire season, delaying the regeneration process. When a severe drought event is observed in regions affected by fires in the following one or 2 years, water-stress conditions will limit photosynthetic activity and net primary production, thus reducing vegetation growth and regeneration.

The recent availability of several long-term remote-sensing datasets for monitoring vegetation conditions opens the opportunity to use them in areas where fire occurrence is high or when less in situ information about vegetation is available. Therefore, studies to assess the robustness of present techniques and their adaption to new indices and sensors are crucial. In this respect, the overall consistency of obtained results with the mono-parametric model of vegetation recovery [16, 20], together with the model simplicity in terms of formulation, anticipates that it may be quite easily adapted to other low-resolution satellite data, as well as to other types of vegetation indices. In the present chapter, an assessment will be made on the portability of the mono-parametric model originally developed using NDVI data from the VEGETATION sensor on-board SPOT [16] with 1 km of resolution by applying the model to NDVI data at 250 m of spatial resolution from the MODIS instrument on-board Aqua and Terra satellites.

2. Data and methods

2.1. Data

The NDVI time series were retrieved from the MODIS Terra V6 product, covering the period February 2000 to June 2017 over a region extending from 36.8910° to 42.3276° N and from 9.8280° to −6.1938° W. The time series used corresponds to the MODIS 16-day (MOD13Q1) product with a spatial resolution of 250 m, supplied on a sinusoidal projection. The pixel reliability index provided with the data was used to eliminate values that did not present the highest reliability level. Monthly composites were obtained using the Maximum Value Composite method [34] and the missing values were linearly interpolated.

Information about land cover was based on the Corine Land Cover (CLC) map, available on a 250-m spatial resolution for Europe and respecting to the years of 2000 and 2006 (http://land.copernicus.eu/pan-european/corine-land-cover/). The CLC classification offers an inventory of surface, with 44 classes of land cover. The thematic maps were resampled to the NDVI-MODIS projection.

2.2. Identification of burnt areas

In the present work, the fire seasons of 2003, 2005 and 2012 were analysed. The identification of burnt areas followed the procedure proposed by Gouveia et al. [16] and Bastos et al. [20]. Burned areas are identified by means of unsupervised clustering of the NDVI monthly anomalies, based on the K-means method [35, 36]. Due to the short number of years of the time series, and in order to mitigate the lever effects of extreme values, monthly anomalies were computed as departures from monthly medians instead of monthly means. Considering that the fire occurrences provoke a very sharp reduction in the NDVI values that persists on the following months [16], the clustering analysis was performed on the following hydrological year, which starts in September [27].

Burnt areas appear associated to the cluster whose centroid presents persistent negative anomalies during the entire vegetation cycle. The number of clusters required to adequately separate between burnt and non-burnt areas is not fixed and depends on several factors, such as the occurrence of a drought episode, which can also reduce NDVI [20]. In this work, four clusters were required in 2012, and three clusters in the remaining years analysed. Burnt areas may present low anomalies of NDVI that persist for more than 1 year after the fire [20], and for this reason burnt pixels from the two previous years were previously identified and removed from the analysis. Results obtained from the cluster analysis were visually compared with the maps of yearly burnt area made available from the National Institute of Nature and Forest Conservation (ICNF), and a very good agreement was found in the case of large burnt scars. **Figure 1** shows the burnt area and the centroids obtained by cluster analysis for the fire season of 2012.

2.3. Model of vegetation recovery

The model of vegetation recovery used in the present work is the mono-parametric model proposed by Gouveia et al. [16] and based on NDVI. The model is given by

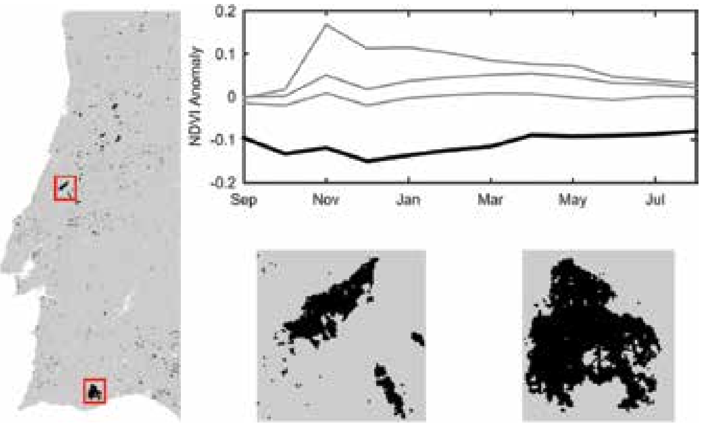

Figure 1. Left panel: Burned areas in continental Portugal during the fire season of 2012 (black pixels in the left panel) as identified by means of cluster analysis and annual cycles of monthly MVC-NDVI anomalies; top-right panel: centroids of the four identified clusters; centroid associated with burned areas is presented in black; bottom-right panel: burned areas selected to apply the recovery model.

$$y(t) = ae^{-bt} \tag{1}$$

where y is the so-called lack of greenness, defined as the departure of NDVI from the so-called Gorgeous Year (GY) that is defined as a hypothetic annual vegetative cycle associated to an ideally healthy state of vegetation. Parameter b in Eq. (1) characterises the recovery time and parameter a characterises the lack of greenness at the time of the occurrence of the fire event, being therefore viewed as an indicator of fire damage. The use of departures of NDVI from GY aims at minimising the impact of the inter-annual variability of NDVI. The monthly values of GY are computed by selecting the maximum value of NDVI in the pre-fire period for each month. Noting that

$$\frac{y(t)}{a} = \frac{NDVI(t) - GY(t)}{NDVI(t = 0) - GY(t = 0)} \tag{2}$$

the value of b is estimated by means of regression analysis performed on the following linear model:

$$ln\left[\frac{y(t)}{a}\right] = -bt \tag{3}$$

The mono-parametric model allows estimating the vegetation recovery time (tR), defined as the period elapsed from $t = 0$ (when the fire took place) up to the time when the modelled curve of y crosses the threshold defined as 90% of the median value in time of the spatially averaged lack of greenness over the pre-fire period.

In this work, the methodology described earlier was adapted to the MODIS Terra V6 product with a spatial resolution of 250 m from 2000 to 2016. The methodology will be applied to NDVI monthly composites for several large burnt areas detected in 2003, 2005 and 2012. Results obtained for 2003 and 2005 will then be compared with the findings by Gouveia et al. [16] and Bastos et al. [20] allowing to assess whether the methodology may also be successfully applied to sensors with a resolution different from the one of SPOT-VEGETATION.

The fire seasons of 2003 and 2005 in Portugal were outstanding, with annual amounts of burnt area substantially larger than the 1980–2002 mean. The exceptional fire season of 2005 further coincided with the 2004/2005 drought, one of the most severe episodes since the early twentieth century [21, 27]. During the hydrological year of 2011/2012, Iberia was hit by another severe drought event. The events of 2004/2005 and 2011/2012 correspond to two of the worst drought episodes, in both magnitude and spatial extent, ever recorded in this semi-arid region [37, 38]. During the hydrological years of 2004/2005 and 2011/2012, drought episodes caused negative anomalies of NDVI over large sectors of Iberia for up to 7 months (out of 11) of the vegetative cycle. While in the case of the drought episode of 2005, the impact on vegetation covered roughly two-thirds of the Iberian Peninsula [21]; in the recent episode of 2012 the *deficit* in greenness affected a more restrictive area located in central Iberia. The effect of drought on post-fire vegetation is reflected by a delay in the regeneration rates, whereas the influence on pre-fire vegetation may be related with the dryness of fuel and on fire damage and severity [21]. The important role of drought on pre- and post-fire behaviour of vegetation strongly suggests also applying the methodology to monitor burnt scars and vegetation regeneration rates to the larger burned areas of 2012 fire season.

3. Results

3.1. Modelling vegetation recovery using NDVI-MODIS and comparison with NDVI-SPOT for 2003 and 2005 fire seasons

The original mono-parametric model to estimate vegetation regeneration times after large fire events relied on 10-day values of Maximum Value Composites of Normalised Difference Vegetation Index at 1-km spatial resolution as obtained from the VEGETATION sensor. In the present work, NDVI monthly values were computed by means of the maximum composite performed using MODIS 16-day (MOD13Q1) with a spatial resolution of 250 m.

After burned scars were identified by means of a cluster analysis on NDVI monthly anomalies (see Section 2.2), the regions to be studied in this chapter were chosen among the ones already selected by the authors in previous works [16, 20] for the 2003 and 2005 fire seasons over Portugal. The burnt scars chosen were the so-called regions I and II by Gouveia et al. [16] from the 2003 fire season (hereafter named R1 and R2, respectively) and the so-called regions RVII and RVIII [20] from the 2005 fire season (hereafter named R4 and R3, respectively). **Figure 2** shows both the location of the four chosen burned areas (left panel) and the corresponding land-cover types, as obtained from CLC2000 (right panel). The fractions of the main land-cover types in the selected burned areas are presented in **Table 1**.

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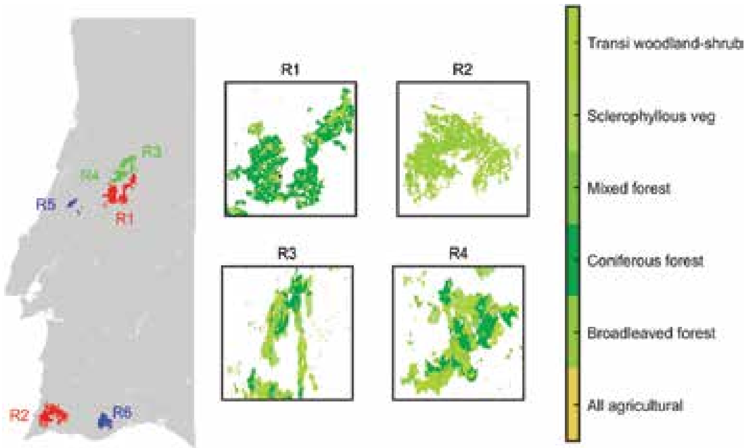

Figure 2. Burnt areas in Continental Portugal in 2003 (R1 and R2) 2005 (R3 and R4) and 2012 (R5 and R6) as obtained by cluster analysis of NDVI anomalies over the year following each fire season (left panel). Selected areas for the present work and respective nomenclature are identified by the rectangular frames labelled from R1 to R6. Corine Land-cover 2000 map for burned areas of 2003 and 2005 at 250 m spatial resolution (right panel).

The comparison of the obtained burnt areas using cluster analysis over NDVI anomalies as obtained using the MODIS dataset with previous results based on NDVI anomalies retrieved from SPOT [16, 20, 21] reveals very similar shapes on both cases, despite the different period of the available NDVI datasets, highlighting the robustness of the methodology used. The slight differences observed may be related with the different spatial resolution and projection of NDVI-MODIS.

It may be noted that, due to the different projection used in MODIS dataset, regions R3 and R4 include some pixels from other regions (i.e. pixels from R3 (R4) in R4 (R3)). **Figure 2** (right panel) and **Table 1** show, as expected, that R1 is mainly occupied by coniferous forest (76%, *P. pinaster*) and R2 by broadleaved forest (59%, Eucalyptus) (**Table 1**). In the cases of R3 and R4, they are mainly occupied by transitional woodland-shrub (around 40% in both cases) and coniferous forest (around 30%) (**Table 1**).

The mono-parametric model was then adjusted to the NDVI-MODIS time series spatially averaged over the four considered regions (**Figure 3**). The vegetative cycle that characterises the

	All agricultural	Broadleaved forest	Coniferous forest	Mixed forest	Sclerophyllous vegetation	Transitional woodland-shrub
R1	4.82	1.42	76.41	3.13	0.00	13.24
R2	3.06	59.18	0.25	0.28	19.96	17.13
R3	3.29	0.48	30.83	3.61	0.00	43.10
R4	1.98	3.41	33.12	5.93	0.00	44.44

Table 1. Main land-cover types, as obtained using Corine Land Cover 2000 classification, that are present in the burned scars selected: R1 and R3 from 2003 and R4 and R5 from 2005.

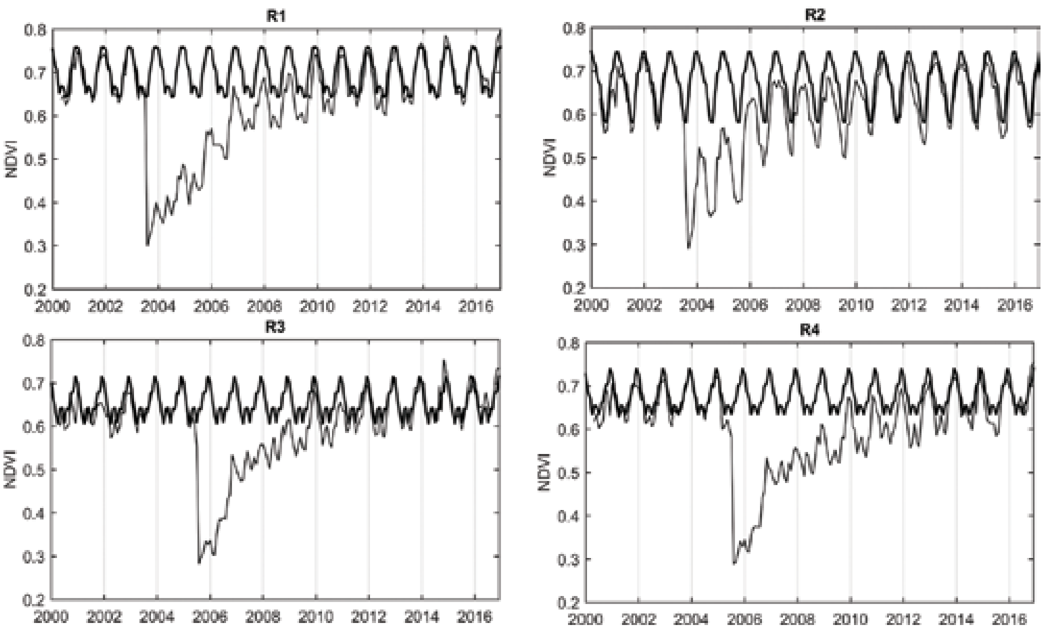

Figure 3. Time series of NDVI (grey curves) spatially averaged over the four considered burned scars: R1 and R2 for 2003 (top panel) and R3 and R4 for 2005 (bottom panel) fire season. Black curves represent the Gorgeous Years (GY) of vegetation, given by the annual cycles of maximum NDVI for each month over the considered period.

dominant vegetation type within the burned area is also shown in **Figure 3**. As expected, the vegetative cycle of vegetation over the R2 region presents a higher inter-annual variability than over R1, which is consistent with the broadleaved dominance in R2. The sharp decay in NDVI time series during the fire season of 2003 (**Figure 3**, top panel) and 2005 (**Figure 3**, bottom panel) corresponds to the loss of vegetation over the considered scars that resulted from the fires.

As described in the previous section, the time required for vegetation recovery (tR) is counted up to the month when the modelled curve of y intercepts the line defined as 80% of the median values of y during the pre-fire period (**Figure 4**). Obtained recovery times (averaged values over each burnt scar) are presented in **Table 2**. When compared with corresponding recovery times obtained in the previous works, estimates obtained with NDVI-MODIS data for scars R1 and R2 fall inside the 95% confidence interval of the previous estimates with NDVI-VEGETATION, whereas for scars R3 and R4 the estimated recovery times are 3 months longer than the upper bound of the 95% confidence interval. However, it should be noted that regions R3 and R4 of the present work include parts of external burn scars not included in RIII and RII of the previous study [20], respectively, and this may contribute to increasing the recovery rates obtained with NDVI-MODIS. On the other hand, the shorter ranges of the 95% confidence intervals obtained for the estimates with NDVI-MODIS are worth being emphasised. This could be associated with the larger post-fire period of available information which allows a better adjustment of the regeneration curve.

It may be noted that Gouveia et al. [16] and Bastos et al. [20] have used 90% of the median (instead of 80%) as the threshold. However, in the present work, when using the MODIS dataset

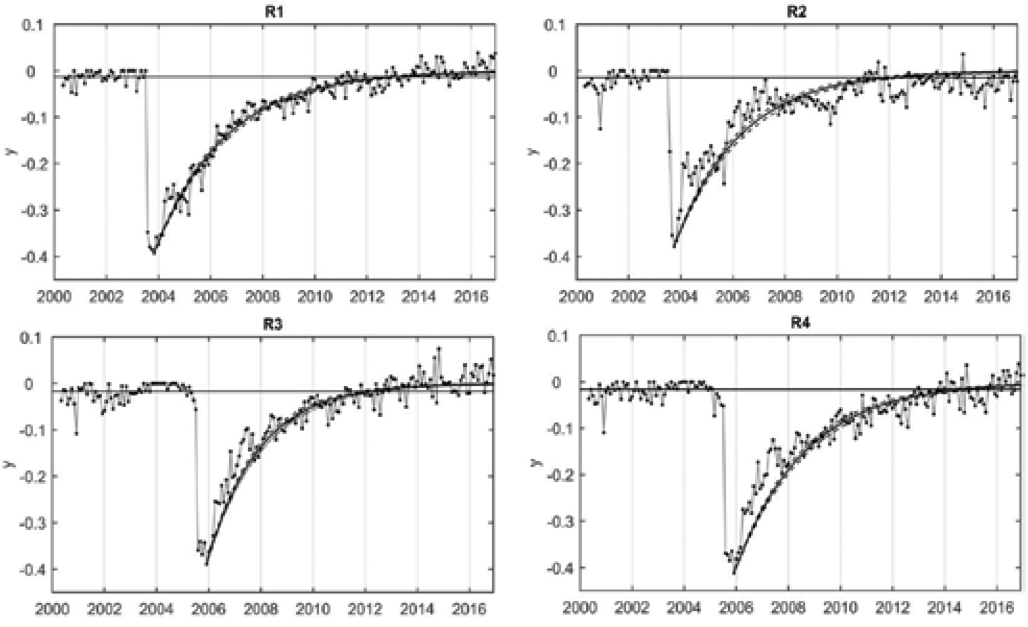

Figure 4. Time series of monthly lack of greenness, y (black line with asterisks) and modelled curve (solid line) of vegetation recovery, spatially averaged over R1 and R2 from 2003 (bottom left panel) and R3 and R4 from 2005 fire seasons (bottom right panel). Dashed lines indicate the 95% confidence limits of the regressed curve.

there is an increase in spatial resolution from 1km to 250m and therefore NDVI values present a less smooth behaviour inside the considered pixel. An additional feature is related with the differences observed for RED and NIR channels for the two sensors (i.e. RED: 0.62–0.67 and NIR: 0.841–0.876 μm for MODIS versus RED: 0.61–0.68 and NIR: 0.78–0.89 μm for SPOT).

Figure 5 presents the spatial distribution of recovery times over R1 and R2 from 2003 (bottom-left panel) and R3 and R4 from 2005 fire seasons (bottom-right panel). A visual inspection reveals a very good agreement between the spatial patterns of vegetation recovery obtained using NDVI-MODIS with the ones obtained in previous works (**Figures 6** and **7** from [1, 2]), when using NDVI-SPOT. Despite the obvious differences in spatial resolution, the spatial patterns of higher (lower)-recovery time values (tR) are located in the same regions.

Despite the different periods covered by the available NDVI datasets, the differences associated with spatial resolution and projection and the slight differences in spectral channels used

	R1	R2	R3	R4
tR (months)	49 [52]	45 [43]	35 [30]	48 [42]
I95(tR) (months)	46–51 [45–59]	42–48 [38–49]	33–37 [28–32]	45–50 [40–45]

Results from [16] in the case of R1 and R2 and from [20] in the case of R3 and R4 are also shown in brackets for comparison.

Table 2. Estimates (tR) and 95% confidence intervals (I95(tR)) of recovery time respecting to the fit by linear regression of the mono-parametric model of vegetation recover on y dataset from NDVI-MODIS for R1 and R2 for 2003 and R3 and R4 for 2005 fire seasons.

to compute NDVI, which contribute to slight differences of NDVI between the two products, the recovery rates estimated when using NDVI retrieved from MODIS dataset with NDVI obtained from SPOT [16, 20, 21] reveal very similar recovery patterns, highlighting the robustness of the methodology used and their applicability to other indices and sensors.

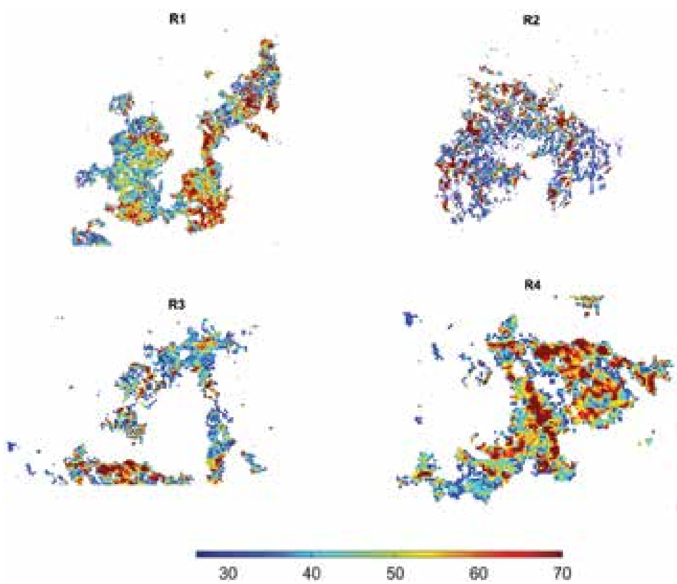

Figure 5. Spatial distribution of recovery times, in months, over R1 and R2 from 2003 (bottom-left panel) and R3 and R4 from 2005 fire seasons (bottom-right panel).

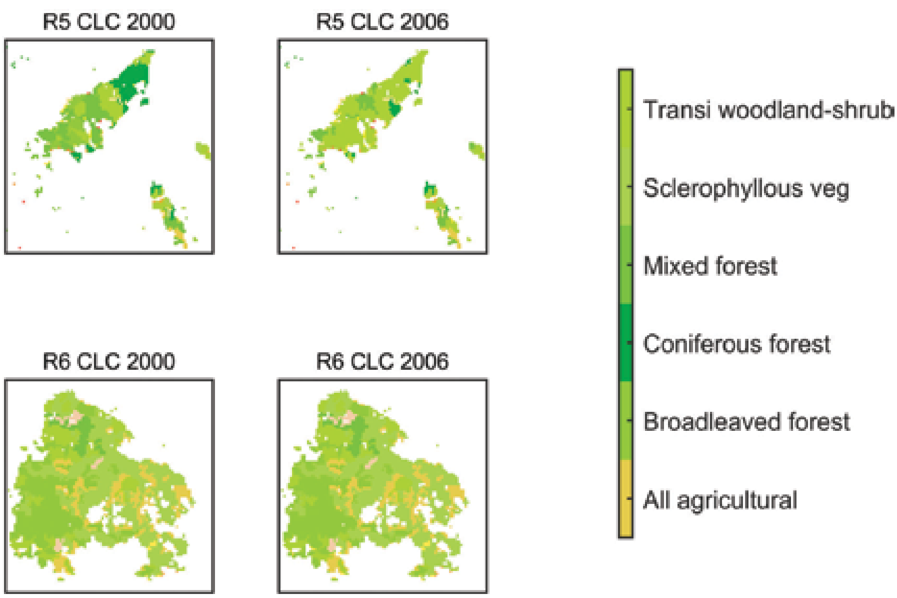

Figure 6. Corine Land Cover 2000 (left panel) and 2006 (right panel) map for burned areas R5 (top panel) and R6 (bottom panel) for 2012 fire season.

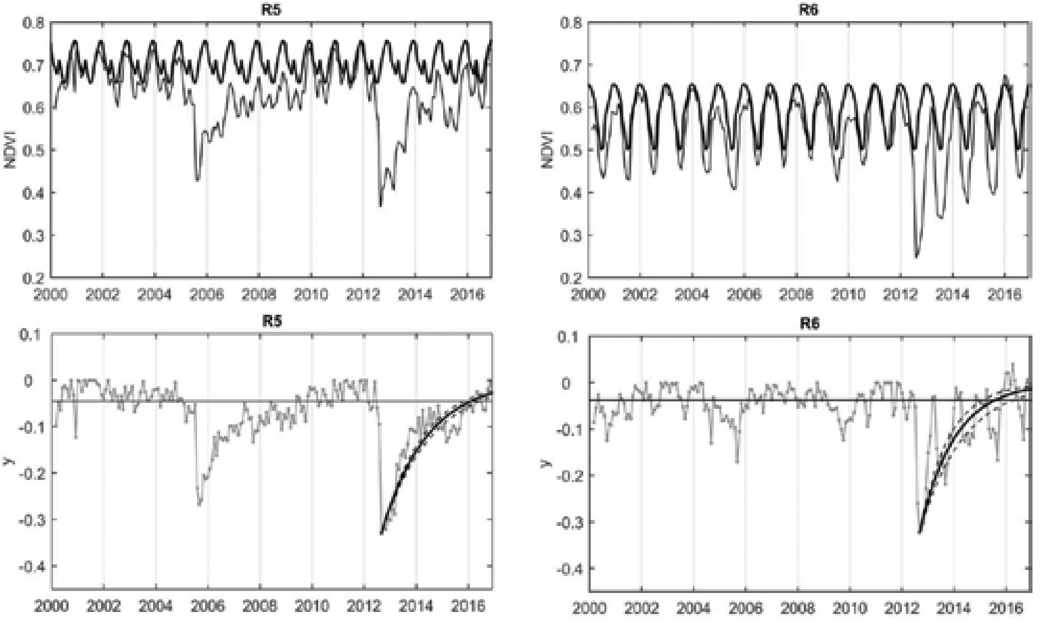

Figure 7. Time series of NDVI (grey curves) spatially averaged over the two considered burned scars: R5 and R6 for 2012 (top panel) fire season. Black curves represent the Gorgeous Years (GY) of vegetation, given by the annual cycles of maximum NDVI for each month over the considered period. Time series of monthly lack of greenness, *y* (black line with asterisks) and modelled curve (solid line) of vegetation recovery, spatially averaged over R5 and R5 for 2012 (bottom panel). Dashed lines indicate the 95% confidence limits of the regressed curve.

3.2. Vegetation recovery after 2012 fire season

The two largest burnt scars obtained by the clustering technique applied to NDVI anomalies of the 2012 hydrological year are presented in **Figure 1**. These two regions are named R5 and R6 (**Figure 2**). Choice of the scars was also motivated by the associated land-cover types, as they are mainly occupied by transitional woodland-shrub type in the case of R5 (around 70%) and by Sclerophyllous vegetation in the case of R6 (around 40%) (**Table 3**). In the region located in the South of Portugal, a considerable number of pixels corresponding to broad-leaved forest (21%), transitional woodland-shrub (21%) and agricultural practices (16%) are also found (**Table 3**). It is the first time that the mono-parametric model is used to study the recovery process in burnt scars mainly occupied by this type of Mediterranean vegetation (Sclerophyllous vegetation).

The mono-parametric model was accordingly adjusted to the NDVI-MODIS time series spatially averaged over the two considered regions (**Figure 7**, top panel). The vegetative cycle that characterises the dominant vegetation type within R6 presents a higher inter-annual variability than for R5, although showing smaller values of NDVI. This feature is in agreement with the dominant types of vegetation that show a very marked vegetative cycle (broad-leaved, grassland and agriculture), but also present less greenness and density typical of the Mediterranean vegetation. The decrease of NDVI values during 2005 in R6 is also worth noting, being consistent with the impact of the 2004/2005 drought event on the vegetation.

		All agricultural	Broadleaved forest	Coniferous forest	Mixed forest	Sclerophyllous vegetation	Transitional woodland-shrub
R5	2000	8.49	10.90	22.29	31.61	1.93	24.43
	2006	8.49	0.21	6.35	14.15	1.38	69.01
R6	2000	15.49	24.17	0.00	3.60	43.07	13.68
	2006	15.14	21.06	1.21	3.25	37.89	21.45

Table 3. Main land-cover types, as obtained using CLC2000 and CLC2006 classifications, that are present in the burned scars selected: R5 and R6 for 2012 fire season.

The sharp decay in NDVI time series during the fire season of 2012 (**Figure 7**, top panel) corresponds to the loss of vegetation over the considered scar that resulted from the fire. However, in the case of R5 a second decrease moment of NDVI is obvious. This feature is a clear indicator that the pixels (or at least some pixels) inside the burnt scar of 2012 have also burned in 2005.

Figure 7 (bottom panel) shows the time series of deviation of NDVI from the GY (y) and the respective modelled curves. The time of recovery is lower in R6 (tR = 20 months, I95[tR] = [17, 25]) than in R5 (tR = 24 months, I95[tR] = [22, 26]). Recovery rates in these two regions are lower than the ones obtained in 2003 and 2005 for regions dominated by forests. However, they are higher than the regeneration rates obtained for burnt areas of 2004 in South of Portugal, also dominated by agricultural and grassland practices [20]. The 95% confidence interval is higher in the case of R6, due to the high variability observed in the time series of y that could be associated to the different vegetative cycles of the several land-cover types that are found in the large area defined as R6. Additionally, as mentioned in Section 2, the definition of vegetation recovery obtained by the adjustment of the mono-parametric model does not assume the regeneration of the same type of vegetation. In the case of R6, the vegetation that recovers from the 2012 fire seasons seems to have different phenological characteristics than in the pre-fire vegetation, which could be associated with the potential enlargement of the transitional woodland-shrub or the replacement of crops by grassland, a typical feature observed after large fires in semi-arid regions [10].

Figure 8 shows the spatial distribution of recovery times over R5 (left panel) and R6 (right panel) of the 2012 fire season. As expected, the recovery time obtained for the majority of the pixels over both regions is about 20 months. However, small spots of recovery rates of about 40 months are observed in both regions and a very few number of values of about 60 months are also present in the R6 region. By visual inspection, pixels presenting high recovery rates were found to be associated with forest (**Figure 6**), where it is common to find such regeneration rates.

Forest fires are recurrent in Portugal due to the accumulation of flammable material and water stress, usually associated with either climate extremes or land-use change [4]. Although well adapted to fire, the vegetation density and composition should be affected by severe fire episodes [8, 13, 18]. The vegetation cycle observed in **Figure 7** over R5, where the occurrence of two fire episodes is conspicuous, one in 2005 and another in 2012, turns this region into a very interesting case study in the framework of recurrent-fires analysis. Therefore, the burnt area classification obtained through cluster analysis for 2005 and 2012 was overlapped and R5 region was analysed in detail. **Figure 9** (top panel) presents the burned areas over the R5 region for 2005 in light grey, for 2012 in dark grey and the overlapped region in black. In **Figure 9** (bottom, left panel), the

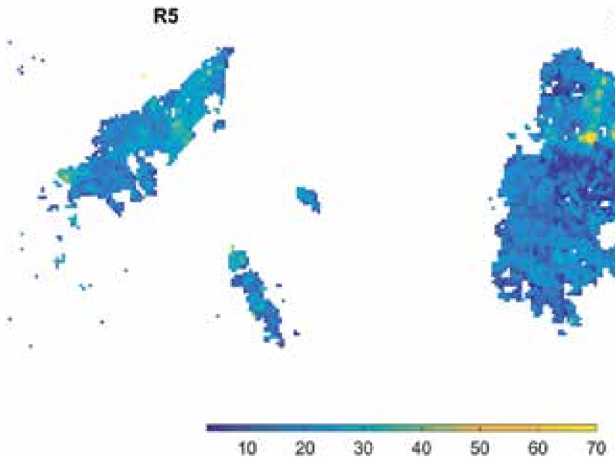

Figure 8. Recovery time in months for the regions R5 and R6.

NDVI (grey curve) represents the spatially averaged values over the area in black (i.e. the area that burned in both 2005 and 2012). The Gorgeous Year, as obtained considering the period until the fire season of 2012, and the time series of the monthly lack of greenness, spatially averaged over the area in black of R5, are also presented. The modelled curves (solid line) of vegetation recovery for the fire season of 2005 and 2012 are represented in red in **Figure 9** (bottom, right panel).

Regeneration rates were also computed for both fire seasons, being longer in the case of the fire season of 2005 (tR = 34 months, I95[tR] = [32, 35]) than in the case of 2012 (tR = 29 months,

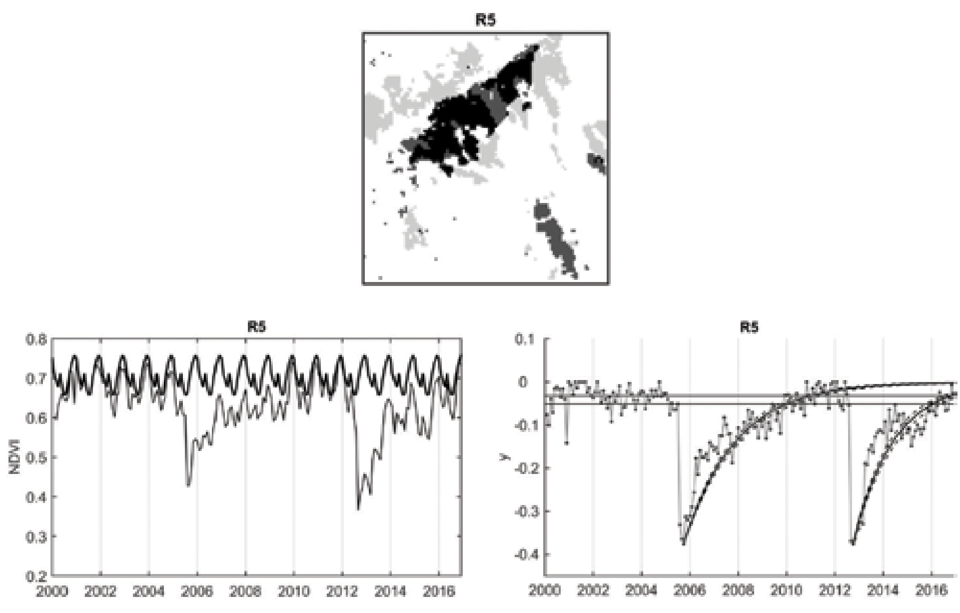

Figure 9. Top: Burned areas obtained through cluster analysis for 2005 (in light grey) and 2012 (in dark grey) over R5 region and overlapped region (in black); bottom: As in **Figure 7** but for the pixels simultaneously burned in 2005 and 2012.

I95[tR] = [27, 32]). As already mentioned, vegetation recovering from the 2005 fire season seems to have different phenological characteristics when compared to the pre-fire vegetation, which are related with the replacement of the existing forest before the fire season of 2005 which occupied around two-thirds of the burnt scar (Broadleaved—11%, Coniferous—22% and Mixed Forest—32%, **Table 3** and **Figure 6**) by transitional woodland-shrub, occupying an area that went from 24% in CLC2000 up to 69% in CLC2006 (**Table 3** and **Figure 6**). This new predominant vegetation type is prone to become dry, namely in the case of the severe drought that occurred in 2012 [4, 21], becoming flammable fuel [22] and contributing to increase the severity of fires and to larger burned areas [39].

4. Conclusions

A mono-parametric model of vegetation recovery in areas affected by large wild fires was assessed in terms of consistency and robustness. For this purpose, vegetation recovery is here modelled based on time series of NDVI from the MODIS instrument (MODIS Terra V6) and results compared against previously obtained ones using data from the VEGETATION sensor [16]. The pre-fire period covered by NDVI-MODIS is 2 years shorter than the one by NDVI-VEGETATION, but a long period of data after the fires of 2003 and 2005 is available, allowing to compare the results obtained with both datasets. In addition, the 250-m spatial resolution of NDVI-MODIS is substantially higher than the 1-km resolution of NDVI-VEGETATION, which may allow to better model the vegetation dynamics and its recovery after a fire episode.

Burnt scars were identified by means of cluster analysis performed on monthly anomalies of NDVI and four previously studied regions, two from the 2003 [16] and two from the 2005 fire seasons [20], were selected to be studied. The fit of the mono-parametric model allowed estimating the time required for vegetation recovery (tR). Despite differences in terms of used datasets, obtained recovery rates when using the NDVI-MODIS dataset presents very similar patterns to the ones obtained with the NDVI-VEGETATION dataset [16, 20, 21] highlighting the robustness of the methodology used and its applicability to other indices and sensors.

The important role of drought on pre- and post-fire behaviour of vegetation has motivated the application of the developed methodology to monitor burnt scars and vegetation regeneration rates to two large burned areas of the 2012 fire season. The regeneration rates obtained through the application of the vegetation recovery model to both burnt scars are lower (around 20 months) than the ones obtained in previous works for regions dominated by forest, but are higher than the recovery rates obtained in regions dominated by agricultural and grassland practices [16, 20]. A detailed analysis of the spatial patterns of recovery times over both regions reveals a large majority of pixels presenting recovery times around 20 months, with some hotspots of pixels presenting 40 and 60 months that are found in regions dominated by forest [20].

One of the studied areas was successively affected by two large fires, one in 2005 and the other in 2012. The regeneration model when applied to the subset of pixels that burned in both 2005 and 2012 pointed to a higher-recovery time for the pixels burned during the 2005 fire than in 2012, although both being around 30 months. The definition of vegetation recovery used in the present work (and proposed in [16]) is based on NVDI and therefore does not assume

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the regeneration of the same type of vegetation. It was found that the pre-fire forest, which occupied around 65% of the burnt scar, was indeed replaced by transitional woodland-shrub, which in post-fire has increased from 24% in CLC2000 to 69% in CLC2006. The predominance of a more flammable vegetation type [22], as well as more sensitive to extreme drought events, will increase the risk of more severe and large fires [39].

The development of reliable techniques to assess post-fire vegetation recovery features in conditions of recurrent fires is crucial for a better understanding of vegetation behaviour and species succession in the Mediterranean region, namely in Portugal, which is recurrently affected by severe fire seasons. The recent SENTINEL program, developed by ESA on behalf of the joint ESA/European Commission initiative GMES (Global Monitoring for Environment and Security), will allow the development of new vegetation products at high spatial resolution (Sentinel-2) that will offer an excellent opportunity for better understanding, monitoring and consequently developing new strategies when dealing with pre- and post-fire events.

The application of the proposed procedure based on a simple mono-parametric model of vegetation recovery in regions prone to extreme climate events such as droughts and where land-use practices have changed significantly will allow the development and implementation of better strategies for fire prevention, management and mitigation before and after recurrent fires, namely fuel hazard assessment, prescribed burning, choice of plant species for reforestation, among others [31, 40].

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Chapter 7

Wood of Coniferous Trees: Reaction to Fire

Linda Makovicka Osvaldova

Additional information is available at the end of the chapter

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Abstract

This thesis investigates the reaction of wood of selected coniferous wood species (pine, fir, spruce, larch) to fire. The fact that coniferous wood might be taken from various parts of the tree, i.e., branches, trunk, or root, is also taken into consideration. We study changes in selected properties in relation to fire—weight loss, relative burning rate, charred layer, and (a)/(b) ratio. Results are then statistically evaluated.

Keywords: coniferous wood, fire, mass loss, testing methods, reaction to fire

1. Coniferous wood in forest fire

Climatic changes in Europe brought about a new phenomenon—forest fires. Fires regularly occur mainly in southern Europe—in Portugal, Spain, Greece, southern France, Croatia, and Mediterranean islands.

Slovakia is no exception—there were 136 recorded fires in 2016 causing the damage of 96,665 €. The worst situation came about in 2012 with 517 fires occurring on 170 ha of forest cover. The material damage came up to 793,860 €.

The most common causes of fires are campfires and the burning of grass, dry vegetation, waste, and trash. Statistics show exact causes of fires, size of the area, and damage done to vegetation. One of the biggest fires on the territory of Slovakia broke out in a hard to access mountain ridge. It was probably caused by unruly guests setting up fire on the mountain ridge near a tourist path. The fire claimed human lives. It emerged in the locality of Krompľa, on the border of Hrabušice and Betlanovce, not far from the national nature reserve Tri kopce. The terrain made it impossible for the fire equipment to reach the area. According to the estimates, 10 ha of forest burnt down. The territory, along with Záhorie, was the area with the most frequent reoccurrence of forest fires even in the past. Although forest fires were quite common in our territory in the past, they were not of such large scale and economic consequences [1, 2].

Due to climate change, the intensity of forest fires has risen. In addition, forest fires are influenced by more factors: slope of forest terrain, cardinal points, wind and fuel—tree types, their age, branch proportion, trunk, and root system.

The thesis treats the issue of fuel response of four selected types of coniferous wood and their reaction to thermal stress in constant conditions. The four types of trees are as follows: Scotch pine (*Pinus sylvestris L.*), European silver fir (*Abies alba Mill.*), Norway spruce (*Picea abies* (*L.*) *Karst.*), and European larch (*Larix decidua Mill.*). These conditions simulate an emerging fire.

Anticipated contribution of the thesis is to recommend fire protection measures based on risk assessment of the type and quantity of fuel in a forest area. The issue became relevant after the wind-whirl in the High Tatras in November 2004 and the subsequent fires in 2005. Of the 13 fires, the largest occurred on July 30, 2005 (e.g., **Figure 1**) [3, 4].

Figure 1. Fire of calamity in High Tatras, July 30, 2005.

2. Overview of current situation

2.1. Wood: flammable material

Wood is obtained mainly from treelike plants. Different parts of the tree (root, trunk, and tree crown) have different functions and usability.

Chemistry in a live tree indicates chemical composition of necrotic cells (cell walls and lumens—intercellular spaces). From a chemical viewpoint, wood is a complicated complex of heterogeneous biopolymers (90–97%) so-called major components accompanied by smaller quantities of accompanying components (3–10%). Main components of wood are represented by saccharide share (65–75%), composed of cellulose (40–50%), and hemicelluloses, plus aromatic share formed by lignin (15–35%). Accompanying (accessory) components of wood are formed by organic substances, monomers and polymers, as well as by inorganic ones. In addition to organic substances, which are an essential part of wood, wood also contains mineral substances creating ash during combustion.

Cellulose is a high molecular polysaccharide consisting of B-D-anhydro-derivate of beta-D glucopyranose (1➔4) [5]. For wood, the average polymerization degree of natural cellulose evaluated viscosymetrically is 4000–5500. One part of cellulose chains remains in amorphous arrangement while continuous transition between crystalline and amorphous share can be observed. Cellulose chains are maintained by hydrogen bonds between hydroxy groups of neighboring cellulosic chains.

Hemicelluloses are composed of heteropolysaccharides with lower polymerization degree (mostly 100–200). The main components are pentose and hexose: L-rhamnose, L-fructose, L-arabinose, D-xylose, D-mannose, D-glucose, and D-galactose. Hemicelluloses are amorphous and contain neutral or acidic cross-linked fibers. Coniferous plants contain glucomannans, the main hemicellulose component. Depending on the type of plant, their amount ranges from 20 to 30% [6]. Lignin is a benzenoid component of some plants containing benzene core with propane chain, phenolic hydroxyl groups, and forms a three-dimensional macromolecule.

2.2. Wood characteristic after thermal degradation

2.2.1. Change in chemical composition

There are materials entering the reaction with oxygen (e.g., metals) or which, in the first stage of heating, change their chemical composition, or the composition of their core building elements, produce flammable gases and begin to burn. Wood belongs to this category too. Main components of wood degrade at different temperatures affecting the whole process of combustion.

Hemicelluloses will decompose under temperatures ranging between 170 and 240°C. They are the least resistant to thermal decomposition. By regulating wood heating, we may achieve reduction of hemicelluloses without reducing its strength, resulting in an increase in dimensional stability of wood [7, 8].

Cellulose is more resistant to thermal stress than hemicelluloses. The decomposition rate of cellulose is moderate up to 250°C. Intensive decomposition of cellulose is observed at the temperatures of 250–300°C. It leads to disruption of links in the main chain according to a radical mechanism; the tail link of cellulose turns into levoglucosan [9].

Lignin is the most resistant to thermal decomposition. Process of the thermal decomposition of lignin is divided into two stages. In the first stage, labile ether alkyl links decompose at the temperatures of 300–320°C. The second stage is an active decomposition of lignin at the temperatures of 350–390°C. The structure of macromolecules is disrupted and volatile products are being released. Formation of volatile products is lower than with cellulose. Decomposition rate is slowing down by increasing the temperature and is followed by accumulation of condensing aromatic structures in the solid phase [10].

Wood exposed to temperatures higher than 288°C (temperature generally assumed as charring temperature) can be divided into five degradation zones [11]. The variety of the decomposition of main wood components and characteristic reactions in different temperature intervals lead to differentiation of burning process into several stages.

2.2.2. Changes in anatomical structure

The anatomical structure itself, individual cell elements, affects the process of combustion, its first phase—ignition—in particular. It results mainly from chemical composition and geometric shape of cellular elements, their size, and their number.

2.2.3. Changes in physical characteristics

In addition to chemical composition, physical properties of wood and wood-based materials significantly influence the course of combustion. Each physical property has an impact on burning, though not to the same degree.

The thesis does not represent a comprehensive assessment of physical properties during wood combustion. The following properties have been chosen: wood density, its surface, moist level, thermal properties, and geometric shape.

The thicker the material is (the same volume, but it is heavier), the more energy is needed for ignition and combustion. Some claims distinguishing flammability levels of woody plants according to their density are wrong. Chemical composition is more important, e.g., woody plants with higher content of hemicelluloses are easier to be ignited even if they have higher density level. With the same chemical composition (same percentage represented by the main wood components), the impact of density on ignition and burning manifests itself. The impact of density on ignitability is more significant with large wood-based materials [12].

Surface of the material (its quality) is another physical characteristic, which significantly affects combustion. Wood, capillary-porous material, is rough on the surface. The roughness depends on working as well as on the anatomical structure of wood. Besides roughness, surface quality also depends on anatomical defects, defects resulting from working, mechanical damage, dirt, etc., changing the surface quality. Surface quality mainly affects thermal conductivity α. The smooth and high-quality surface reflects the energy of radiation source and

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flame source thus making it more difficult for the wood to be ignited compared to the rough surface under the same test conditions.

From the point of view of quality, working is as important as the color of wood. The natural color of the wood (including tropical woody plants) comprises the entire color range. Thermal degradation causes color changes. The light color of wood gradually darkens and finally turns black, charred layer. The intensity of darkening depends on heat rate and temperature—several authors treated the subject. The color change is brought about by polysaccharide degradation (hemicelluloses and cellulose). The final stage, creation of charred layer, occurs in every single case. The charred layer is of black color, a good absorbent of thermal radiation. Its chemical composition and porous structure is, at the same time, a bad heat conductor. Therefore, charred layer represents auto-retarding nature of wood, which is taken into consideration in practice.

Color change also influences wood quality. Charred layer is formed due to changes at all levels: changes in chemical composition, supermolecular structure, anatomical structure, as well as macroscopic structure. An interesting study was introduced by who monitored changes in chemical composition of wood immediately after removing the charred layer [13].

As mentioned above, charred layer has an auto-retarding character and plays a role in the process of wood burning of load-bearing structures. We assume that it will play its role in forest fires too, but it is not clear whether this property will have positive or negative impact. As the fire progresses, charred layer remains in relatively cold environment preventing the girder or other wooden building elements from burning. During forest fire, charred layer smolders mostly in the root system situated in overheated soil. Environment cools down very slowly. Air flow is caused by climatic conditions, or is caused by temperature differences caused by the fire. This flow can also bring about secondary combustion of unburnt fuel (e.g., **Figure 2**).

2.3. Coniferous wood in forest fires

Forest fire is an extremely harmful factor that is detrimental to all components of forest biocenose, biotope as well as plant and animal component. It is a sudden, partially, or fully uncontrolled time and space-limited emergency event, which has a negative impact on all social functions of forest. It causes direct and indirect damages and, according to the method of its development, it belongs to anthropogenic (which are more common in Slovakia) or natural harmful factors. It is a complex of physico-chemical phenomena based on unstationary (changing in space and time) processes of combustion, gas exchange, and heat transfer [14].

In general, forest fires are mainly caused by natural conditions and man himself. They are often caused by human negligence, failure to observe fire protection measures—no fire, no smoking, no grass burning, no brushwood burning, playing with matches, etc.—or by underestimating the danger when making an open fire. Cases of arson are very rare.

Figure 2. Color change of wood and its estimated thermal degradation (after removing charred layers, cuts of 1 mm in thickness have been made).

In addition, these fires are more dangerous since they occur in the areas which are hard to access for fire brigade and their equipment, with insufficient or unfit resources of water for fire fighting purpose, and require enormous deployment of people, special fire, or aviation technology [15].

According to the type of flammable substances, forest fires belong to class A, fires of solid substances of organic origin. Forest fire can be characterized as a process of burning of the whole array of organic materials which form forest cover. At temperatures of 80–150°C, water in the tissue and wood is lost. At the wood self-ignite is at the temperature of about 300°C. At the temperatures above 450°C, gases, which are being released from wood, ignite in contact with the outside air and at the temperatures above 600°C, wood itself becomes a source of combustion. During burning, temperature of flame comes up to 700–800°C. In the process of burning of a tree crown of coniferous tree, temperatures rise up to 1000°C with the height of the flame up to 100 m. In the process of burning of coniferous forest, the temperature of the flame comes up to 1300°C.

Forest fires are divided according to different criteria. In forestry as well as fire practice, they are most commonly divided into:

- underground fires,
- ground fires, and
- ring fires.

The above-mentioned types of fires are described in details. Fire in the area hit by wind-whirl has its own specific features, which do not allow its unequivocal inclusion into the above-mentioned classification. A new category has been formed, fire of devastated area. This type of fire is characterized as follows:

- Surface of the fire is not differentiated according to height as in the above-mentioned division; it is made up of broken wood, uprooted trees, standing trees, remnants of decaying trees (dead wood), herb cover, and forest floor.
- Distribution of wood material is uneven, wood is stacked in layers several meters high "including" parts of tree crowns with assimilation apparatus also in ground layers.
- After processing such wood, a large number of logging waste remains in the area representing a potential risk resulting in formation and spread of fire.
- Ignition followed by combustion may be area-wide, long-term (lasting several days), throughout the whole area of the fire, not only in its "head" (principle of a bonfire or "pyre").
- Devastated area is, compared to other types of fire, difficult to access because of temporary cessation of forest transport networks and piled-up wind-throw mass.

Therefore, it is imperative to be aware of all aspects and risks of forest fires, their development and behavior, system of prevention, monitoring, modern, effective, ecological, economic and safe fire-fighting methods as well as consequences and methods of their elimination or clean-up [16].

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3. Wood: flammable material

The thesis treats the issue of forest fires, explaining causes of its formation and rapid development. Its objective is to examine the reaction of different conifers to forest fire. Forest fires (ring, ground, and underground fires) were quite common on other continents, but nowadays, they are becoming a problem in Europe too, particularly its southern regions. Fire in devastated area has not been mentioned in any foreign written source. In the area affected by wind-whirl, the "forest" (blown down trees) is burning but in a different form and in a different way than with common forest fires. Results of the thesis may be incorporated into fuel models that can model this type of fire for fire and rescue services. Heat sources and conditions of the experiment characterize change in wood properties during its thermal degradation. Branch, trunk, and root have been exposed to these heat sources and their influence on the development of fire has been observed.

The goal of the thesis is to find out, assess, and compare the reaction of selected coniferous woody plants to conditions simulating fire. Fire in the experiment is seen as forest fire. This is given by the selection of tree parts (branch, trunk, and root), which means all forms of fuel are represented such as crown, above-ground, ground segments as well as fire of devastated area.

Thermal stress represents one source of ignition. Homogeneity of the source—one heat, radiant source has been designed for this purpose so that the results were comparable and selected evaluation criteria were influenced by the fuel type only.

Distance—position of fuel (test specimen) from the heat source was chosen so that the temperature of the source may manifest itself and, at the same time, the sensitivity of the measurement has been ensured. Therefore, the difference between the distances is 5 mm only.

Evaluation criteria—are the fundamental changes in physical parameters (weight loss, thickness of charred layer, relative burning rate, and (a)/(b) ratio—represents relative burning rate divided by the time the highest relative burning rate was measured).

The given criteria, qualitative selection of fuel and evaluation criteria shall determine the sensitivity of the selected coniferous woody plants to the reactions simulating fire conditions.

Phrasing of those objectives of the thesis is based on several initiatives, including, in particular, my personal experience, as well as the discussions and tutorials with experts of state administration bodies and many experts from practice.

When drawing up the doctoral thesis, several methods of research were used: analysis, synthesis, abstraction, comparison, induction, and deduction.

In the initial stage, analysis, comparison, and synthesis were used, whereas in the final phase, the methods of induction and deduction, comparison and subsequent formulation of regularities of the given phenomena have been applied [17].

Using system approach, the research of the thesis has been carried out in the following three stages:

- Collection, sorting, and data processing

All necessary information has been obtained from various sources. We utilized all available resources from documentary records and bibliographic research to bibliographic literature, scientific articles from professional journals, proceedings from various conferences, information from various seminars, scientific and research thesis, reports of state administration and other institutions, internet resources and, last but not least, personal tutorials or other forms of communication with officers of some state administration bodies and institutions (in particular Department of Fire Prevention, County Departments of Fire and Rescue Services, Faculty of Wood Sciences and Technology in Zvolen). While sorting, studying, and processing the information, analytic, and synthetic method have been used, contributing to the subtheoretical knowledge and conclusions.

- Synthesis of partial results

After further sorting, partial results of analyses performed provide basis for formulating synthetic knowledge in the given field.

- Application of acquired knowledge

In the final phase, the knowledge and conclusions we came up with were arranged in mutual contexts so as to provide and enable theoretical and practical applicability while improving the phenomena monitored.

4. Methods

4.1. Coniferous wood after thermal degradation

Test specimens were made up from four selected types of coniferous woody plants: Scotch pine (*Pinus sylvestris L.*), European silver fir (*Abies alba Mill.*), Norway spruce (*Picea abies* (*L.*) *Karst.*), and European larch (*Larix decidua* Mill.).

Test specimens were prepared from 1-m-long trunks (pine, fir, spruce, larch). After dressing the trunks—removing the bark and cutting it into boards—the process of drying to constant moisture of 8 ± 2% followed. The boards of 10×12×150 mm were then cup up. No surface finish was used for the test specimens. Test specimens from branches and roots have been cut in the same way as the trunk. The diameter of the branches and roots was 60 mm. See **Figures 3–7**.

Figure 3. Scotch pine (*Pinus sylvestris L.*).

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Figure 4. European silver fir (*Abies alba Mill.*).

Figure 5. Norway spruce (*Picea abies (L.) Karst.*).

Figure 6. European larch (*Larix decidua Mill.*).

4.2. Heat load

4.2.1. Apparatus

Simple device—consisting of scales, asbestos boards (to protect scales against heat radiation), stand, support frame, radiant heat source (radiator), and clamp holder for test specimens—was used for the experiments.

The apparatus (e.g., **Figure 8**) is composed of electronic weighing scales, Sartorius Basic plus type BDBC from Sartorius AG Company, I. class of accuracy with non-automatic weighing instruments, measuring with an accuracy of two decimal places and the maximum weight 2100 g [18].

Figure 7. Testing samples.

4.2.2. Radiant heat source

Infrared heater is used as a heat radiation source. Heat transfer from the heater was carried out by diffusion of electromagnetic radiation of 0.75–12 Jm of wavelength which is, after being absorbed by a solid, transformed into heat. Infrared heater of T-5 class by Electro Prague was used for the experiment. The heater is of a flat shape, bent slightly into arch shape in the direction of the longitudinal axis of the body. Radiation was given off by the front side, back side, and front edges of the heater. Side edges of the heater were neglected due to their low significance in heat transfer. The emitting body is made from special ceramics, cordierite. The material is highly resistant to sudden changes of temperature with differences in temperatures greater than 70°C as well as resistant to high temperatures (1100°C).

The emitting body is equipped with a thin aluminum parabola. Electromagnetic radiation is common in the nature as every single body emits it. Wavelength or frequency depends on the temperature of the solid. As the temperature of the solid changes, its color changes as well [18].

Dimensions and parameters of the heater (e.g., **Figure 9**):

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Figure 8. Apparatus.

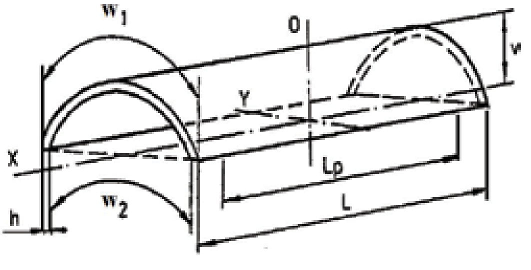

Figure 9. Dimensions and parameters of the heater.

Total length: l = 245 mm

Working length: lp = 200 mm

Outer width: w_1 = 85 mm

Inner width: w_2 = 64 mm

Thickness: h = 5 mm

Height: v = 30 mm

Temperature (30 mm from the radiator): t = 130°C

4.2.3. Test procedure

Test procedure is as follows. Heater has been warming up for 15 min. After 15 min, a sample has been mounted into the clamp holder and exposed to radiant heat for 3 min. For each woody plant type, 15 tests will be conducted. time will be constant: set to 3 min. The only variable is the distance from the heater—30, 35, 40, 45, and 50 mm. For every single specimen, weight loss will be recorded after 15 s and relative burning rate will be calculated. In case the test specimen ignites, it will be put off after 3 min. Each test specimen will be measured before the test, including its thickness. After cooling down, charred layer will be determined. Charred layer will be removed up to the healthy/undamaged wood.

4.3. Evaluation criteria

4.3.1. Weight loss

Weight loss will be recorded while the sample is exposed to the radiant heat source. Relative weight loss will be calculated according to Eq. (1) [18].

$$\delta_m(\tau) = \frac{\Delta m}{m_{(\tau)}}.100 = \frac{m_{(\tau)} - m_{(\tau+\Delta\tau)}}{m_{(\tau)}}.100 \ [\%] \tag{1}$$

where $\delta_m(\tau)$ is the relative weight loss in time (τ) [%], $m_{(\tau)}$ is the weight of the sample in time (τ) [g], $m(\tau + \Delta\tau)$ is the weight of the sample in time $(\tau + \Delta\tau)$ [g], and Δm is the difference in weights [g].

4.3.2. Charred layer

Charred layer will be determined, and the thickness of charred layer will be calculated as the ratio of original thickness of test specimen and the thickness of test specimen after the test. The percentage will be determined according to Eq. (2) [18].

$$\Delta h = 100 - \left(\frac{h_1 - h_2}{h_1}.100\right)[\%] \tag{2}$$

where Δh is the thickness of charred layer after the test/thermal stress [%], h is the thickness of the test specimen before the test [mm], and h_2 is the thickness of the test specimen after the test [mm].

4.3.3. Relative burning rate

Relative burning rate is determined according to Eqs. (3) and (4) [18]:

$$v_r = \left|\frac{\partial \delta_m}{\partial \tau}\right| [\% \ s^{-1}] \tag{3}$$

or numerically.

$$v_r = \frac{\left|\delta_{m_{(\tau)}} - \delta_{m_{(\tau+\Delta\tau)}}\right|}{\Delta\tau} [\%\ s^{-1}] \quad (4)$$

where v_r is the relative burning rate [% s^{-1}], $\delta_{m(\tau)}$ is the relative weight loss in time (τ) [%], $\delta m_{(\tau + \Delta\tau)}$ is the relative weight loss in time ($\tau + \Delta\tau$) [%], and $\Delta\tau$ is the time interval at which weights are subtracted [s].

4.3.4. (a)/(b) ratio

Relative burning rate is an important figure; however, it is also important to know when, throughout the experiment, the peak of relative burning rate was measured. If this value is measured at an early stage, it is a material which contributes to the development of fire in an intensive way. If this happens in the final stage of the experiment, this material will have a more positive assessment. The ratio between relative burning rate and the time necessary to achieve its highest value was used in several experiments and test methods for fire protection purpose. Experimental device measured both types of data, so the thesis presents the ratio between relative burning rate (a) and the time necessary to achieve its peak (b) which has given the name to "(a)/(b) ratio," which is numerically multiplied by 106 so that the figure had better information value.

4.4. Statistical evaluation

Data obtained are processed using Statistica 7 program. Multiple factor analysis of dispersion has been used. When using multiple factor analysis of dispersion, we observed the effect of several qualitative or quantitative factors (in the given discrete values) on the values of the observed property of wood (weight loss, charred layer, the relative burning rate, and (a)/(b) ratio). In our case, the factors are as follows:

- distance of heat source from the sample,
- type of coniferous trees,
- time recorded every 15 s.

In case we prove that factors are interrelated (time and distance), their statistically significant effect will be assessed by regression analysis, see Eq. (5). [18]

$$y = ax + b \quad (5)$$

where a is the time and b is the evaluation criteria.

5. Results

To make it clear, measured values are shown in the tables.

Average values of all measurements are shown in **Table 1**.

Wood	Place	Distance [mm]	Weight loss [%]	Charred layer [%]	Relative burning rate [% s^{-1}]	Max. relative burning rate [s]	(a)/(b) ratio [% s^{-2}]	Density [kg m^{-3}]
Pine	Branch	30	13.82	23.23	0.001242	160	7.76	444.83
		35	11.88	19.63	0.000869	150	5.79	451.41
		40	7.15	7.95	0.000564	130	4.34	455.94
		45	5.46	4.58	0.000413	140	2.95	463.40
		50	4.63	3.21	0.000372	82.5	4.51	435.76
	Trunk	30	71.56	100.00	0.008611	137.5	62.63	418.22
		35	14.53	15.03	0.001259	162.5	7.74	425.94
		40	13.71	9.12	0.001244	157.5	7.90	400.93
		45	9.41	6.05	0.000708	85	8.33	391.35
		50	6.98	2.51	0.000559	102.5	5.45	398.76
	Root	30	25.38	40.45	0.002707	142.5	19.00	440.58
		35	17.28	21.51	0.001972	167.5	11.77	439.43
		40	9.07	18.07	0.000834	152.5	5.47	429.81
		45	6.49	10.71	0.000641	167.5	3.83	414.79
		50	5.43	8.35	0.000448	160	2.80	412.95
Fir	Branch	30	15.20	23.92	0.001400	110	12.73	561.81
		35	10.33	17.89	0.000774	140	5.53	546.63
		40	7.34	10.27	0.000520	112.5	4.63	543.30
		45	5.16	6.40	0.001469	155	9.48	541.09
		50	4.02	4.90	0.000404	167.5	2.41	539.75
	Trunk	30	67.64	84.70	0.008461	147.5	57.36	418.78
		35	18.09	20.21	0.001654	175	9.45	442.31
		40	11.35	7.37	0.000913	145	6.30	500.71
		45	7.74	4.17	0.000644	142.5	4.52	503.22
		50	6.27	2.96	0.000510	155	3.29	483.78
	Root	30	29.34	42.14	0.004161	162.5	25.60	519.61
		35	13.62	21.47	0.001324	167.5	7.90	508.48
		40	11.54	18.66	0.001427	170	8.39	521.02
		45	7.37	9.55	0.000663	175	3.79	515.31
		50	5.60	7.67	0.000518	172.5	3.00	512.15

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Wood	Place	Distance [mm]	Weight loss [%]	Charred layer [%]	Relative burning rate [% s⁻¹]	Max. relative burning rate [s]	(a)/(b) ratio [% s⁻²]	Density [kg m⁻³]
Spruce	Branch	30	14.73	20.10	0.001217	142.5	8.54	646.95
		35	10.05	14.25	0.000801	130	6.16	589.27
		40	7.00	6.01	0.000564	137.5	4.10	609.73
		45	6.11	2.96	0.000411	145	2.84	635.59
		50	4.79	2.14	0.000445	140	3.18	2.14
	Trunk	30	86.55	100.00	0.009462	110	86.02	351.65
		35	34.38	36.32	0.001213	162.5	7.47	368.28
		40	17.77	22.94	0.001692	165	10.25	345.98
		45	9.56	5.15	0.000774	120	6.45	358.82
		50	8.34	4.84	0.000657	100	6.57	337.61
	Root	30	30.48	44.40	0.002491	150	16.61	463.25
		35	15.07	22.16	0.001506	162.5	9.27	470.60
		40	11.00	17.79	0.000913	140	6.52	560.57
		45	5.46	9.79	0.000398	132.5	3.01	483.82
		50	5.24	5.65	0.000494	160	3.09	475.86
Larch	Branch	30	14.73	21.44	0.001235	105	11.76	633.71
		35	10.05	18.24	0.000986	95	10.38	568.48
		40	5.61	10.70	0.000507	175	2.90	612.67
		45	5.47	5.65	0.000398	175	2.28	628.42
		50	3.43	2.49	0.000387	75	5.15	618.09
	Trunk	30	36.21	29.64	0.004450	147.5	30.17	434.46
		35	12.68	12.42	0.000994	145	6.85	447.53
		40	10.35	7.53	0.000866	127.5	6.79	445.06
		45	7.35	3.06	0.000599	130	4.61	457.69
		50	6.83	1.58	0.000579	140	4.14	445.85
	Root	30	23.73	37.20	0.002533	170	14.90	470.46
		35	13.72	24.62	0.001199	167.5	7.16	482.56
		40	10.14	19.45	0.000943	130	7.25	482.59
		45	6.29	11.37	0.000873	167.5	5.21	482.24
		50	4.59	6.95	0.000639	180	3.55	506.80

Table 1. Average values of all measurements [19].

5.1. Evaluation and discussion

Monitored evaluation criteria have been assessed from two aspects: woody plant type and its position. Final evaluation is represented by dependence between the evaluation criteria. Size of charred layer, relative burning rate, and (a)/(b) ratio relate to weight loss, and the dependence between them is evaluated.

In all cases, it is a linear dependency. Graphic statistical evaluation is shown in **Figures 10–12**. In **Figure 10**, the correlation relationship between weight loss and charred layer for all types of woody plants and all positions is depicted. Linear dependence is given by the value r^2, which is equal to 0.948, the value close to 1. Such close dependencies are also found with the other evaluation criteria. **Figure 11** represents a correlation between weight loss and relative burning rate $r^2 = 0.922$ and **Figure 12** shows the correlative relation of weight loss and (a)/(b) ratio where $r^2 = 0.944$. These figures show the dependency evaluation for all measurements, regardless of the position and the type of woody plant. **Tables 2** and **3** show the equations of regression in linear form for each correlation, evaluation criteria, types of woody plants and their position.

In general, it is possible to conclude that the trunk of spruce showed the worst values given the criteria, which is necessary to be taken into account from the fire fighting point of view. There are also differences between positions within one type of woody plant. This means that when reviewing the fuel in devastated area, it is necessary to assort the quantities of fuel.

5.2. Theoretical and practical contribution

Scientific contribution of the thesis is to complement the data that characterize the fuel monitored for fire protection purpose. Meeting the target consists on finding out certain values that can be applied into computer models of fire. The thesis provides instructions for further experimental

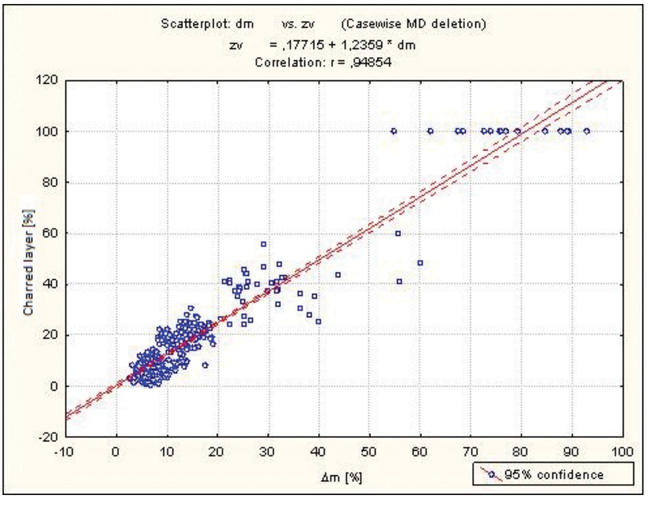

Figure 10. Correlation relations of weight loss and thickness of charred layer for all measurements (woody plants and their positions).

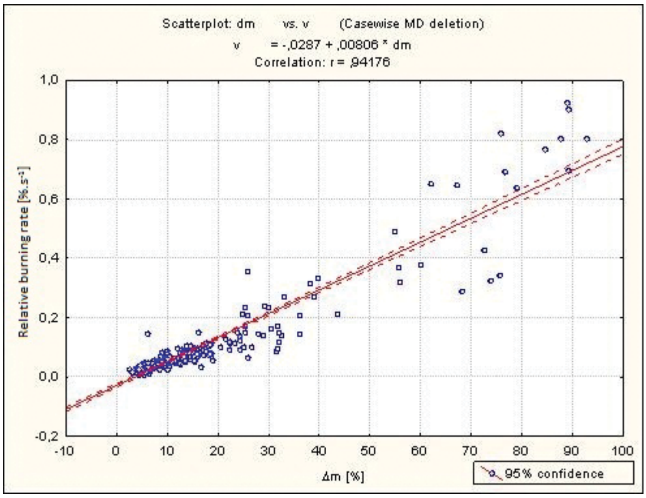

Figure 11. Correlation relations of weight loss and relative burning rate for all measurements (woody plants and their positions).

work that could be diversified into other measurements, research into further physical changes, or chemical properties of selected woody plants and their parts. The conclusions of these recommendations could then answer the question of why there are differences within a single woody plant and why there are differences within the same group of woody plants, coniferous woody plants. Moreover, evaluation of parameters of other non-wood parts seems crucial since they may contribute to rapid development of forest fire (needle layers, leaves, groups of shrubs, etc.).

A practical contribution lies in finding other properties of fuel, specification of the risks that are taken into account within operational plans, and projects for risk assessment of forest fire

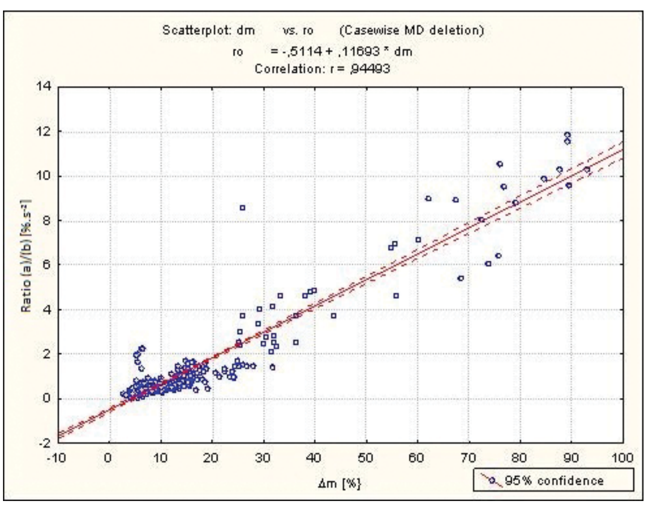

Figure 12. Correlation relations of weight loss and (a)/(b) ratio for all measurements (woody plants and their position).

Criterion	Woody plant	Regression equation	Value of r^2
Thickness ofcharred layer [%]	Pine	y = 1.3824x − 1167	0.959
	Fir	y = 1.2993x − 0.2893	0.960
	Spruce	y = 1.1652x + 0.26212	0.974
	Larch	y = 0.94483x + 3.3748	0.772
Relative burning rate [% s^{-1}]	Pine	y = 0.0098x − 0.0346	0.959
	Fir	Y = 0.0051x + 0.0001	0.839
	Spruce	y = 0.0095x − 0.0488	0.949
	Larch	y = 0.0061x − 0.0053	0.852
(a)/(b)ratio [% s^{-2}]	Pine	y = 0.1226x − 0.6248	0.939
	Fir	y = 0.0998x − 0.173	0.750
	Spruce	y = 0.1279x − 0.6566	0.964
	Larch	y = 0.0855x − 0.2591	0.811

Table 2. Regression equation in linear form and the r^2 value for correlations of evaluation criteria for the given types of woody plants.

Criterion	Position	Regression equation	Value of r^2
Thickness of charred layer [%]	Branch	y = 1.6639x − 2592	0.855
	Trunk	y = +1.2902x − 5718	0.972
	Root	y = +1.4117x + 1.7700	0.949
Relative burning rate [% s^{-1}]	Branch	y = 0.0048x + 0.0032	0.581
	Trunk	y = 0.0085x − 0.0415	0.902
	Root	y = 0.0059x − 0.0025	0.708
(a)/(b) ratio [% s^{-2}]	Branch	y = 0.0619x + 0.0061	0.534
	Trunk	y = 0.1236x − 0.7564	0.952
	Root	y = 0.0905x − 0.1389	0.464

Table 3. Regression equation in linear form and the value of r^2 for correlations of evaluation criteria in the given positions.

or devastated area. On the basis of the above-mentioned procedures, the readiness and amenities of fire-fighting units in certain locations will be optimized. Quality evaluation of woody plants will help to ensure that, in addition to forestry assessment of the suitability of woody plants (i.e., into fire-fighting belts), it will also use other assessment such as fire-fighting.

6. Conclusion

Forest fires have always been a part of people's life on our territory. They are quite common even today and their "quality" as well as their quantity changed for the worse. They are more extensive, more difficult to extinguish in terms of intervention and fire-fighting procedures, especially in our mountain areas. Special fire-extinguishing equipment as well as aviation technology must be used. The difficulty level of intervention, its length as well as economic costs have changed. The problem needs to be dealt with comprehensively (as in every single field of multidisciplinary fire protection) meaning that it needs to be dealt with not only by using modern equipment, tactics but also by studying fuel and by conducting further scientific research.

This thesis should contribute to this solution. Evaluation of individual woody plants (found in various types of literature) was carried out for fire protection purpose assessing wood as building material. Woody plants were divided into hard and soft and/or broad-leaved and coniferous trees. The first hypothesis of our experiment supposed certain degree of homogeneity between the selected coniferous trees, or between different tree parts (branch, root, and trunk) within a single woody plant. Confirming this hypothesis (homogeneity) would mean expressing certain value that could be incorporated into model software programs of forest fire modeling (e.g., FireSite).

However, it turned out the second hypothesis has been correct: there will be differences between the selected woody plants and differences within a single tree type. This hypothesis resulted from the contrast of the first one as well as from personal experience of fire-fighters and boy scouts. Fire-fighters run into problems while extinguishing underground fires (root system burning) and every boy scout knows that to make a good bonfire, wood from root system is needed. To come up with a complex solution, all three parts (branch, trunk, and root) were suggested which is given by tree physiology. During forest fires, trunk is in a different position than when dealing with devastated area fire where trunks are in "horizontal" position. Amount of fuel of different quality (branch, root, and trunk) is possible to identify, to some extent, from forest management plans on the basis of forest cover density, age of the tree, location, growth, etc. Parameters such as how individual components of wood react to heat, fire, and how quickly they contribute to development of fire were missing. This thesis should complete these data.

The thesis results confirmed the second hypothesis: there are differences between different types of conifers such as pine, fir, spruce, and larch, even in the position within the tree (branch, trunk, root). Surprisingly, the worst results have been recorded for the most common woody plant—spruce. All parameters that have been monitored reached their peak for this tree type. Weight loss, as one of the selected parameters, was chosen since the change in this physical property represents standard and basic assessment criteria of materials which are tested for fire protection purpose. Charred layer, formed in the process of burning, a property of wood that is very welcome in wooden constructions (its auto-retardant nature, mainly in the process of burning of root system), indirectly represents the length of its burning, or more precisely smoldering. This effect is very dangerous in terms of re-ignition of forest fire.

Other monitored properties, such as relative burning rate and (a)/(b) ratio, characterize certain speed at which material shall contribute to development of fire. These four selected types of observations were statistically evaluated the way it is referred to in the previous chapter.

The results are comparable with literature, in particular in terms of charred layer thickness and burning rate. Only data for spruce wood and its trunk can be compared with other literature. Other parts of woody plants, such as branch and root, are not described in any available literature. This also applies to other types of woody plants that we monitored and which have been described for wood practice purpose, not for fire protection purpose. This thesis brings new knowledge of the above-mentioned woody plants and their behavior in fire conditions.

Such comprehensive solution can make it possible to fight forest fires that are common in our territory.

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Edited by Janusz Szmyt

This book concerns the different aspects of forest fires, the impact of fire on both forest resources (e.g. forest cover) and communities that use different forest functions. Therefore, forest fires have their environmental, economic and social consequences, and none of them is less important. Forest fires can be caused by both natural forces and anthropogenic factors, and in the latter case, it is extremely interesting to profile the potential arsonist. Forest fires may also cause conflicts, stronger or weaker, in local communities that have been using forests for years. These conflicts can be solved both by gradually changing the law itself and through education at the local level. Not less important is the ability to detect fires early, which can be helped by the development of modern technologies. In limiting the effects of forest fires, it may also be helpful to develop mathematical models that indicate various factors affecting the possibility of a fire or affecting the rate of its spread. Not less important is the attempt to assess the direction of forest regeneration after the fire has ceased, in understanding what the help of modern technology is. These aspects of forest fire are the subject of this book. I realize, however, that the contents in it can only be an incentive for the reader to learn more, in an interesting aspect.

I assume that this book will be valuable to researchers as well as students who are interested in different aspects connected to forest fires, not only from the ecological point of view but also from the social one. Both are extremely important in future forest protection and sustainable use of forest by local communities.

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