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RESEARCH PAPER

Determining response times for the deployment of terrestrial resources for fighting forest fires. A case study: Mediterranean – Chile

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Abstract

M.E. Castillo, and F. Rodriguez y Silva. 2015. Determining response times for the deployment of terrestrial resources for fighting forest fires. A case study: Mediterranean – Chile. *Cien. Inv. Agr.* 42(1): 97-107. A study of response times for the arrival of terrestrial forest fire fighting resources was undertaken. The advantage of the method proposed here is that it may be exactly replicated in different countries and under different environmental conditions, budgets and infrastructures for wildfire combat. This is an international-level support offering better reference material for optimizing terrestrial resources. In the combat of forest fires, fire fighting resource response times are of particular importance when evaluating fire advance speed and fire damage potential against time. Due to the importance of speed in fire containment and the economic consequences of a fire, a fire combat response time curve was constructed using fire fighting operation data from 1,006 fires that occurred in a Mediterranean region of Chile. Five categories were established according to fire size and fire behavior and were based on the conditions of the perimeter fire control strategies. The results show different fire evolution curves for affected areas. In fires less than 1 ha in size, the first fire fighting attack lasted on average 25 min, compared with up to 69' for fires approximately 20 ha in size. The affected surface area ranged from 0.97 to 11.43 ha over these size ranges. The response time decreased for fires greater than 20 ha, mainly due to the predominance of aerial resources that accelerate the first fire fighting attack. The average burnt area ranged from 11.43 to 31.92 ha, which suggests good combat efficiency, given that these fires present very aggressive behavior. Mathematical functions were derived from this analysis, which describe fire fighting tasks in terms of fire advance time. This innovative study, for which there are no other references in scientific literature, will allow cost and efficiency functions to be derived for forest fire combat, among other benefits. As indicated earlier, the advantage of this research is that the methods may be perfectly adapted to the operative conditions faced by an organization during the wildfire season. Knowledge of response curves enables optimization of financial resources to increase terrestrial coverage of the protected area.

Key words: Extinction times, forest fire, fire combat, fire behavior.

Introduction

The protocols and mechanisms for defense and control usually employed to contain and extinguish

fires are closely linked to the time involved for each combat phase, whether by aerial or terrestrial means. In general, fire spread exhibits a geometric increment under favorable fire spread conditions, whether in situations of uncontrolled propagation or when fire fighting methods are applied. There-

fore, the key factor in all fire control strategies is to calculate the maximum time needed to contain the fire perimeter at a reasonable environmental, social and economic cost. Fire spread risk is directly linked to this maximum time and is usually affected by topography (slope and exposure), fuel type, properties of advance and control speed, climatic and meteorological conditions (Ntairo *et al.*, 2004; Hu and Ntairo, 2009), as well as accessibility of major fire outbreaks in terms of distance from and feasibility of firefighting appliances (Fried *et al.*, 2006). Using this information, a fire may thus be classified according to affected area, fire transfer or spread time and the fire fighting methods applied to each combat phase. Nevertheless, fieldwork studies such as those undertaken and published by Julio *et al.* (2012) have shown that no forest fire is exactly the same, however similar the initial conditions and variables that influence fire development. In other words, two or more fires exhibiting the same initial conditions of combustibility, propagation danger, environmental and topographical conditions can behave very differently. As indicated earlier, these differences in fire spread, whether uncontrolled or using fire fighting methods, can therefore be studied by evaluation and calculation of the point at which different combat phases and fire fighting strategies should be employed. This is critical considering that in terms of fire behavior, fire progression is calculated as a rate of geometric advance, whereby every minute of uncontrolled fire advance results in an increase in the danger of fire propagation. This is why the analysis and comparison of different forest fires is necessary to establish mathematical relationships that allow fire behavior variables and associated costs to be calculated according to the rate of fire advance. This study evaluates different forest fires, classified according to size and operating conditions for the fire fighting and combat phases, to construct equations according to the categories of control time and affected surface area. As there are no formal references in scientific literature that provide a breakdown of the time lapsed for

combat phases, the rules obtained here form the first references for establishing predictive equations in terms of fire size, advance speed and costs of fire-fighting operations.

Materials and methods

Study area

The investigation focuses on an area of central Chile, between 32°-38°S (Figure 1), where approximately 85% of all the country's forest fires occur. This area is characterized as having a Mediterranean climate with a marked fire season in summer. Fires in this area average 10.2 hectares in size, and almost 100% of these fires are caused by humans, either deliberately or through the irresponsible use of fire. Various fire prevention strategies and systems have been developed in this territory, which has a notable efficiency in combat and level of training of fire fighting staff in both the private and public sectors.

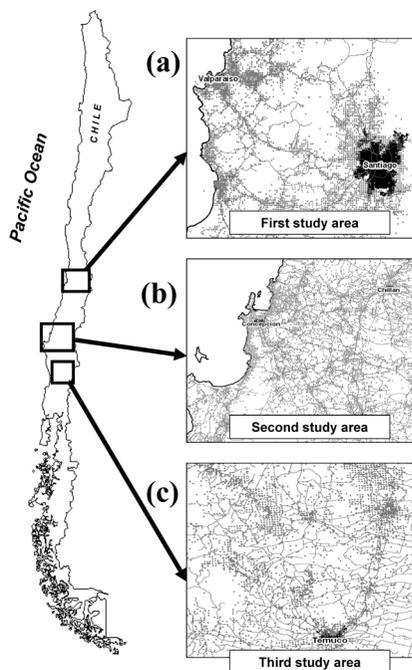


Figure 1. Study area

Data collection

The study used records from the official database of the National Forestry Corporation (CONAF) that detail the combat of fires that occurred between 1997 and 2012 in central Chile. In particular, data on the affected burnt area, duration of each combat phase and operational unit costs were compiled and expressed in US dollars. The data were refined by checking their reliability and identifying missing or incorrect information. Due to the extreme variability in the behavior of each fire and fire spread risk conditions, the study focused on records that shared similar conditions of topographic, fuel and meteorological input data. In practice, the input data were validated in the field by registering the start and end conditions under which each fire spread.

Fire combat phases

Various stages or phases of activity may be identified in fire fighting operations, and these are generally carried out in sequence: Reconnaissance, First Attack, Control, and Settlement (also known as Extinction). In exceptional cases, Surveillance or Ember Control is also included as the final phase (Julio, 2007). In this analysis, detection is included as an earlier stage that concentrates on fire suppression tasks (fire fighting activity), and whose purpose is the timely discovery and location of potential forest fires.

Detection. This describes activity that aims to monitor an area under protection with the purpose of identifying and tracking forest fires that may have started. Detection is the first step in a process that begins with a prompt extinction of fire outbreaks. The speed of detection is extremely important because the difficulty and effort required for fire control increase in line with the time elapsed since the start of the fire.

First attack. This phase is also known as Containment of the Main Outbreak or Initial Attack and

refers to the first act of fire containment on the fire perimeter (Hirsh *et al.*, 2004). It should be noted that this description omits mention of the importance of an earlier stage (due to insufficient data for analysis) known as Fire Reconnaissance, which is fundamental for ground operations as it allows evaluation of current fire behavior conditions prior to planning initial combat strategies (Ntaimo *et al.*, 2012; Rachaniotis and Pappis, 2012). If any information exists regarding the length of time between the Arrival and Reconnaissance phases or between the Reconnaissance and First Attack, it would be extremely useful for this type of analysis. In the first instance, the normal and logical step is to attempt to contain the outbreak that is causing the most problems. That said, this classification is not only based on fire behavior in terms of propagation model and speed, but can also be determined by effect values especially when referring to populations or human lives. At this point, the defined fire reconnaissance strategy will already have been employed because it is sometimes inconvenient to commence activity on the main fire outbreak when damage to other sectors caused by propagation speed can be limited.

Control. This takes place once the main blaze has been contained and involves surrounding the fire area with a safety fireline or perimeter to stop its spread. It is not always necessary to construct this line around the entire perimeter of the affected area because there are often natural features, roads or paths that may be used for this purpose. On the other hand, depending on available resources, fire size and the fire fighting strategy used, firelines may be constructed simultaneously for different blazes in different sectors of the perimeter.

Settlement (also known as the *Extinction* phase). This phase occurs when continuing outbreaks in fire-affected areas are put out, by extinguishing flames and embers, to prevent re-ignition. In theory, settlement starts once the fire has been controlled (Minas *et al.*, 2012). However, this activity may begin before this point, depend-

ing on the availability of resources and the location of those areas still burning (Martell, 2007; Thompson and Calkin, 2011). Control and settlement may often be carried out in parallel. In addition, it is not strictly necessary to carry out settlement across the entire fire-affected area. When this area is very extensive, it is sometimes sufficient to extinguish the embers within a belt at least 50 m wide, from the control line inwards (Julio, 2007).

Data and process

The study considered 1,006 fires that took place in the study area from 1997 to 2012. Among these, those fires with reliable background information about time elapsed and areas affected for each stage of fire combat were selected. In this case, the following criteria were evaluated: combat phases and affected area (Plucinski *et al.*, 2007).

Of the selected fires, combat phases that could be measured and analyzed were defined, taking into account the duration of each phase as well as the size of the area affected. An earlier analysis also included the cost variable, which is essential for quantifying and evaluating the different stages of combat more precisely. In all cases, analysis focused on the use of terrestrial resources, due to reliability of the data obtained and because analysis of aerial resources requires consideration of other variables, especially those related to fires of a greater size. To provide a graphic representation of the results, the graphic model of Parks (1964) was used, and the main combat stages were described using a chart that relates burnt area to time elapsed. Different graphs were constructed to show the behavior evolution for each fire size category defined in this study.

The activities described here begin with the

identification of the first stage in the database, which was defined as the start in the Detection phase for statistical purposes. Later in this phase, the operation center is notified, resources are deployed to a point close to the fire and then transported from the point of arrival to the first fire fighting sector. This is the typical sequence of events for land-based fire fighting activities. Planning for wildfire suppression is one of many ways to help increase the efficiency of a forest fire-fighting organization. Pre-suppression planning and analysis involves assessing how many resources to use, where to locate them, and how they will be dispatched (Wilson and Wiitala, 2003). For aerial control methods, other factors are involved, including arrival time radii, which depends on the aircraft type and specific conditions that may arise before and during the flight as well as the subsequent arrival at the site of the fire (Plucinski *et al.*, 2012). Taking this into account and using the data available, combat phases were analyzed to review the times associated with each component and to form a statistical association between these times and the affected areas. A crucial element in the study of fire evolution is undoubtedly the affected area and its perimeter because these depend directly on a group of topographical and environmental variables including wind (velocity and direction) and the type of fuel (type, quantity, condition, structure and composition) across which the fire spreads (Marianov and ReVelle, 1991; Kirsch and Rideout, 2005). In this analysis, the data were separated into five groups to minimize the mathematical effect of variance and standard deviation for the results of the burnt areas for all the data considered. Thus, fire frequency distribution was reviewed briefly, which resulted in the identification of five large groups based on fire size (Table 1). Each category interval was defined by constructing a surface histogram using frequency analysis to distinguish the data groups.

Table 1. Parameters for the relationship between the burnt area and the number of minutes elapsed per combat phase.

Combat phase	Fire size (ha)	Time elapsed (min) ¹	Standard deviation (e.g., x)	Burnt surface area (ha)	Standard deviation (e.g., y)
Detection	< 1	2	0.76	0.02	0.01
Initial attack		25	8.23	0.66	0.39
Control		49	8.32	0.97	0.07
Settlement		87	23.27	1.00	0.02
Detection	1 – 5	3	2	0.03	0.02
Initial attack		32	18	0.69	0.85
Control		105	54	2.67	1.06
Extinction		160	67	2.96	0.40
Detection	5.01 – 20	3	2.12	0.03	0.02
Initial attack		69	33.01	3.25	3.09
Control		437	614.71	11.43	5.23
Settlement		1,149	543.22	12.08	4.01
Detection	20.01 – 50	2.46	2.02	0.02	0.02
Initial attack		45.69	3.88	3.84	4.03
Control		355	805.30	31.92	7.51
Extinction		1,369.84	1,217.33	33.00	3.50
Detection	> 50	4	4	0.04	0.04
Initial attack		29	15	3.26	6.38
Control		2,004	645	130.10	61.60
Extinction		3,610	1,068	144.00	38.00

¹Time elapsed for each phase is considered as an accumulated average for each database registry.

Results and discussion

The analysis of fire fighting intervention time and fire advance is presented in five categories organized by fire size (Table 1). In each case, the mathematical relationships that yield average times for each phase are included (Table 2), as well as reference or statistical behavior for fire evolution in terms of operative resources.

a) Fires of 0.01 – 1.00 ha

These fires form a small proportion of the fires in natural vegetation, generally scrubland and grass-

land, that frequently occur in highly connected or wildland-urban interface areas. The protocol for resource deployment and rapid response to these fires allows a first group to be defined, which is not necessarily less serious. In certain cases, small areas have led to serious problems of fire containment due to topographical and combustible fuel issues, despite rapid access to the affected areas. The first analysis group, which considers area and advance time in stages, is illustrated in Figure 2 (case 'a'). In line with this analysis, result normalization is presented as an average threshold of 33 min and an average affected area of 1.05 ha; these data may vary slightly if a larger amount of reliable data is considered in the sample.

Table 2. Statistical estimations for each fire size class.

Fire size (ha)	Equation	<i>r</i>
< 1	$\rho = \frac{1}{1 + e^{3.6099 - 0.1839\phi}}$	0.69
	$\rho = 0.1776 - 0.2755 * \ln(\phi)$	0.72
1 - 5	$\rho = 2.9511 * \{1 - e^{-0.017\phi}\}$	0.70
	$\rho = 0.6096 + 0.6312 * \ln(\phi)$	0.72
5.01 - 20	$\rho = 13.3553 * \{1 - e^{-0.0062\phi}\}$	0.75
	$\rho = 2.6411 + 2.1914 * \ln(\phi)$	0.77
20.01 - 50	$\rho = 33.5618 * \{1 - e^{-0.0073\phi}\}$	0.74
	$\rho = -6.9566 + 5.7714 \ln(\phi)$	0.78
> 50	$\rho = 141.225 * \{1 - e^{-1.256\phi}\}$	0.84
	$\rho = 37.3407 - 20.8243 * \ln(\phi)$	0.81

where:

ρ = Burnt surface area (in hectares).

ϕ = Time elapsed (min from detection).

r = Correlation coefficient.

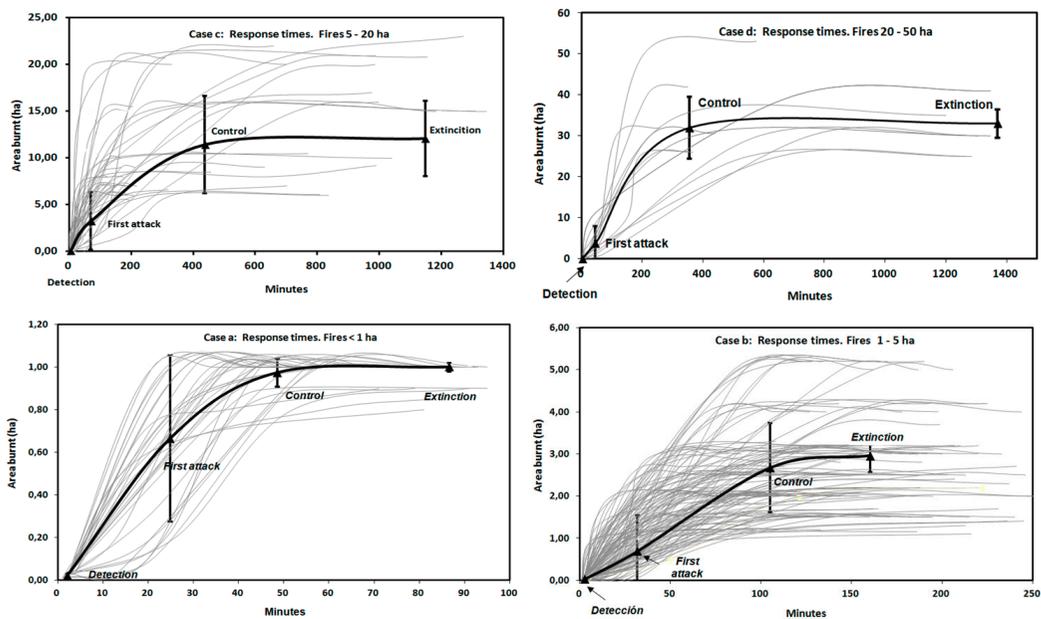


Figure 2. Response times by class (fire size), in minutes and hectares.

b) Fire sizes of 1.01 – 5.00 ha

These fires correspond to very aggressive outbreaks of fire, which in many cases require the greatest resources for fire fighting, especially aerial resources. Although the database does not clearly specify the degree of seriousness for fires of this size, reviewing the spatial location of the outbreak makes it possible to verify the coherence between the affected area and the high level of resistance to control displayed by the type of combustible fuel and topographical conditions reported in the fire records. Similar to the other size categories, these results show a type of logarithmic tendency that is in agreement with Figure 2 (case 'b'). The high dispersion in the data cloud corresponds with the stochastic behavior of the fire under conditions in which it is difficult to compare fires. Here, it is important to verify a general tendency and in this case, a coefficient of determination of 0.64 may be considered as a first valid approximation for studying this type and size of fire.

c) Fire sizes of 5.01 – 20.00 ha

This range mainly includes fires that spread rapidly and, in this case, as observed in practice and in the database review, refers to yellow or red alert events. In both cases, due to accessibility factors, erratic fire behavior and technical aspects of combat operations, the movement of resources has focused on protecting properties and the services associated with the population located in the wildland urban interface. A smaller proportion of fires analyzed here link to fire spread with defense activities in open areas where there is a predominance of scrubland, grassland and dense native vegetation (Figure 2 (case 'c')).

d) Fire sizes of 20.01 – 50.00 ha

This refers to a scant proportion of fires (the 13 most important were considered in this category)

that cover more extensive processes in the phases between detection and extinction due to their size range. The most relevant characteristic is the average response time observed in the control phase, which is less than the size category 5.01 and 20.00 ha for this sample (Figure 2 (case 'd')). Contrary to expectations, the specific conditions for each fire do not always correlate to a greater or lesser time in perimetral control when only considering the relationship between area and time. On occasion, there are other elements that contribute to facilitating or completing fire fighting tasks. In this case, even though the average time from detection to control fluctuated by 355 minutes, the perimetral extinction phase culminated in a cumulative time of approximately 22.8 h, far higher than the category below.

e) Fires greater than 50.00 ha in size

Fires categorized as red alert, which require the most resources to be deployed for fire fighting and the construction of defense barriers, were considered. For all cases analyzed, there were perimetral sections that were contained by the existence of natural barriers and/or the intervention of previously constructed paths or firebreaks. These fires are very aggressive and cause extensive damage, insofar as the average size of events produced in the region ranged from 3.41 ha for 1,006 fires (1997-2011). In addition, a comparison of the size categories indicated that the extent of the average burnt area is extremely variable, with maximum values of approximately 100 hectares (2.78% of all fires analyzed). The tendency for fires of greater size is illustrated in Figure 3.

Intervention by terrestrial and aerial resources and the number and timing of these interventions directly influence the average distribution of the times calculated here for the five classes of fire size. In Chile, the arrival time of the first terrestrial resource fluctuates over a range of approximately 15 – 25 minutes, depending on outbreak conditions, accessibility of the region or commune, available methods and priority criteria for initial

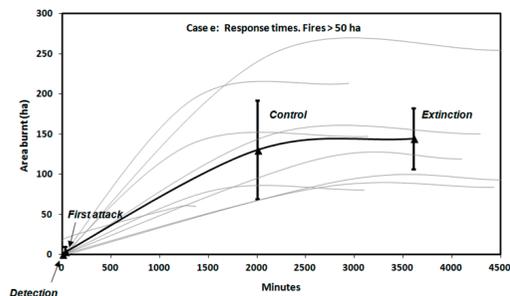


Figure 3. Response times. Tendency for fires of greater size

deployment. With respect to the dispatch of aerial means, the arrival time is established according to the influence radii. In general, a value of 15-30 minutes or less is considered useful for supporting fire fighting activities (Arienti *et al.*, 2006; Haight and Fried 2007; Lee *et al.*, 2012). In the references determined here and the mathematical expression of a damaged area with respect to time, stages were identified in which fire spread increases at a variable rate. The average values for fire advance speed measured in the field ranged between 40-300 $\text{m}^2 \text{min}^{-1}$, reaching values greater than 600 $\text{m}^2 \text{min}^{-1}$ (3.2 ha h^{-1}) under extreme rates of spread. This generally happens when meteorological and topographical conditions, combined with highly flammable affected vegetation, result in an extreme increase in the maximum rate of spread (Kourtz 1989; Mees *et al.*, 1994; Donovan and Rideout, 2003). Typical cases of this phenomenon occur in Chile in wildland-urban interface areas and in the presence of dense scrubland.

Regarding the above discussion and the results presented here, the allocation of fire fighting resources may be further studied from the perspective of the costs involved and the analysis of the efficiency of perimeter fire control. The com-

bination of fire fighting methods and deployment possibilities, which were used in the references calculated here (Table 3), varies according to the local fire spread conditions and the maximum times for stopping fire spread.

As a final point, it may be noted that the study of mathematical references in forest fires provides useful information for further improvement of deployment strategies for terrestrial and aerial means for the combat of forest fires. The deployment strategies are usually regulated based on priority with respect to the seriousness of the fire and budgetary constraints, especially when dealing with numerous fires.

The equations proposed here relate the duration of fire fighting activities and the burnt area under various danger conditions and potential impact of fire spread. These equations generate time thresholds for improved monitoring of resource deployment, the costs involved in extinction operations and a dynamic evaluation of the damage caused by fires.

In general, the most damage is caused by a small proportion of fires, but their vast size requires an exhaustive review of the best strategy for resource deployment, both terrestrial and aerial. The five size categories proposed here provide the first guidelines for monitoring fires according to spread level and anticipated danger potential. Using the derived equations, these guidelines can be applied in resource deployment operations. This is the first study of this type in Chile, and these results can be adapted to other countries considering local and territorial conditions related to forest fires.

Table 3. Relationship between fire size categories and fire fighting resources, and the associated reference.

Size category (ha)	n (1,006 fires)	%	α^1	Combination of resources ²	Associated reference
< 1.00	781	77.6	1,713.24	2 brigades of 8 fire fighters, 1 helicopter	$\rho = 0.1776 - 0.2755 * \ln(\phi)$
1.00 – 5.01	157	15.6	15,480.98	4 brigades, 1 fire engine or truck, 1 helicopter	$\rho = 2.9511 * \{1 - e^{-0.0176\phi}\}$
5.01 – 20.00	40	3.98	82,281.51	4 brigades, 1 plane or 1 helicopter	$\rho = 13.3553 * \{1 - e^{-0.0062\phi}\}$
20.01 – 50.00	14	1.36	242,082.75	4 brigades, 2 fire engines or trucks, 2 helicopters, 1 plane.	$\rho = 33.5618 * \{1 - e^{-0.0073\phi}\}$
> 50.00	15	1.46	1,628,442.49	All available resources	$\rho = 141.225 * \{1 - e^{-1.2566\phi}\}$

¹ α : The average value expressed in US\$ of direct damage caused by the fire, grouped into five types of fuel models: commercial radiata pine plantations, commercial Eucalyptus plantations, native trees, native scrubland and grassland mixed with scrubland. Information source: Castillo (2013).

²All types of fire fighting methods deployed per size category.

Resumen

M.E. Castillo y F. Rodriguez y Silva. 2015. Determinación de tiempos de respuesta en la llegada de recursos terrestres al combate de incendios forestales. Estudio de caso: Chile Mediterráneo. Cien. Inv. Agr. 42(1): 97-107. En el combate de incendios forestales, los tiempos de respuesta de los recursos de extinción adquieren especial relevancia cuando se evalúa la velocidad de avance del fuego y los daños potenciales que se producen a medida que transcurre el tiempo. Por la importancia que adquiere la rapidez en la contención del fuego y sus consecuencias económicas, se efectuó un estudio de curvas de respuesta de los medios de extinción, basados en una base de datos de operaciones de combate de 1.006 incendios localizados en un área mediterránea de Chile. Se establecieron cinco categorías de tamaño y sus relaciones con la evolución del comportamiento del fuego en condiciones de aplicación de labores de control perimetral. Los resultados muestran distintas curvas de evolución en avance de la superficie afectada. En incendios menores a 1 ha, el primer ataque se produce en promedio a los 25 minutos, llegando hasta 69' para incendios cercanos a 20 ha. La superficie afectada oscila entre 0,97 y 11,43 ha para este rango. Los tiempos de respuesta disminuyen a partir de clases de tamaño mayores a 20 ha, principalmente por el predominio de medios aéreos que aceleran el primer ataque al incendio. Las superficies medias ascienden de 11,43 a 31,92 ha en área quemada, lo cual supone una buena eficiencia en el combate dado que se trata de incendios de alta conflictividad en el comportamiento del fuego. De este análisis se construyeron funciones matemáticas que permiten describir el desarrollo de las labores de extinción en función del tiempo de avance del fuego. Es un estudio innovador, y del cual no existen otras referencias en la literatura científica. Permite entre otros beneficios, establecer funciones de gasto y eficiencia en el combate de incendios forestales.

Palabras clave: Comportamiento del fuego, fases del combate de incendios, incendio forestal, tiempos de extinción.

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