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RESEARCH ARTICLE

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Quantitative analysis of forest fire extinction efficiency

Miguel E. Castillo-Soto[*1] and Francisco Rodríguez-Silva[2]

[*1] *Forest Fire Laboratory. University of Chile. Santiago of Chile.* [2] *Fire Management Laboratory. University of Córdoba, Spain*

Abstract

Aim of study: Evaluate the economic extinction efficiency of forest fires, based on the study of fire combat undertaken by aerial and terrestrial means.

Area of study, materials and methods: Approximately 112,000 hectares in Chile. Records of 5,876 forest fires that occurred between 1998 and 2009 were analyzed. The area further provides a validation sector for results, by incorporating databases for the years 2010 and 2012. The criteria used for measuring extinction efficiency were economic value of forestry resources, Contraction Factor analysis and definition of the extinction costs function.

Main results: It is possible to establish a relationship between burnt area, extinction costs and economic losses. The method proposed may be used and adapted to other fire situations, requiring unit costs for aerial and terrestrial operations, economic value of the property to be protected and speed attributes of fire spread in free advance.

Research highlights: The determination of extinction efficiency in containment works of forest fires and potential projection of losses, different types of plant fuel and local conditions favoring the spread of fire broaden the admissible ranges of a, φ and Ce considerably.

Keywords: Forest fire; Combat efficiency; Productivity analysis.

Abbreviations: FCS; Superficial Contraction Factor.

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Correspondence should be addressed to Miguel Castillo Soto: migcasti@uchile.cl

Introduction

Throughout the course of a forest fire, it is of the utmost importance to constantly track and evaluate firefighting activity, because the rate of fire advance normally progresses geometrically in line with costs and potential damage (Rothermel, 1972; de Torres *et al.*, 2012). The size of the area affected by the fire is directly related to the efficiency of combat tasks (Andrews & Queen, 2001; Leone *et al.*, 2009), and in other cases with free advance (Burgan & Rothermel, 1984), that is, where there are no lines of defense, or because there is a particular combat strategy which depends on fire danger conditions. Therefore, combat strategies and the amount of work necessary to bring the fire under control within an established time objective according to certain management guidelines, thus depend on fire behavior and forecasts. This phenomenon, which corresponds with the combined effects of physical and mechanical characteristics (Alexander, 2001; Andrews *et al.*, 2003) observed in environments affected by fire spread, can be modeled mathematically by studying the factors which impact the ratio of size, shape and rate of fire advance (Andrews *et al.*, 2003; Burgan & Rothermel, 1984). Normally, in Mediterranean climate ecosystems and under extreme meteorological conditions where there is a constant wind presence and slope effect, the rate of spread grows geometrically throughout fire duration (Andrews, 1986; Andrews & Queen, 2001; Alexandrian *et al.*, 1999), which is why the attack time for the first arrival of firefighting methods, is of extreme importance (Rodríguez y Silva, 1999; Andrews *et al.,* 2003; Castillo *et al.*, 2013). This rate of progression has been studied from the perspective of potential damage caused by fire advance, such as reported by Rodríguez y Silva *et al.,* (2014) when determining combat operations priority phases according to duration, among other indicators. However, there are not sufficient study references for this phenomenon in relation to efficiency of combat resource allocation. This work is traditionally carried out using classic patterns of dispatch of aerial and terrestrial means, to try and contain the fire advance perimeter in as short a time as possible.

As individual fires usually differ greatly, the study of a sample of actual forest fires from a Mediterranean area of central Chile was undertaken. Data obtained from these fires corresponds to the area, burnt perimeter, size category and average rate of fire advance. Using these records, it was possible to construct efficiency functions for combat costs based on the criteria of economic efficiency.

In the field of fire economics, Homes and Calquin (2013) applied the Cobb-Douglas efficiency model to evaluate firefighting operations linked to the supply of combat support methods and machinery inputs and their relationship to production associated with different levels of input, expressed as the number of meters of fire control lines built each day. In terms of productivity, this seeks to analyze the various levels or elasticity of demand in production (linear meters) associated with percentage changes in supply factors (inputs which in this case are fire control equipment). This analysis is extremely useful for regulating the cost-damage ratio with economic efficiency (Pedernera & Julio, 1999; Molina-Martínez *et al.*, 2011; Rodríguez y Silva *et al.*, 2014). However, as described by Prestemon *et al.*, (2008), this model has the disadvantage of high variability of input factors and as a consequence, has difficulty in establishing a production efficiency range.

In Chile, this analysis is imperative due to the fact that practically all decisions concerning the allocation of methods for fire extinction are based on personal experience (Castillo *et al.*, 2014), but without economic efficiency criteria. For this reason, the central objective of this research was to build the most reliable mathematical representation possible, of those factors which directly influence economic efficiency of firefighting, and whose decision variables are supported by the computational simulation based on Chilean models of fire spread (Castillo, 1998; Rodríguez y Silva *et al.*, 2010), extinction costs and the range of surfaces of those fires considered in the study area. The results form the first formal references available in Chile for this type of study and may be replicated in other conditions of Mediterranean climate, changing the chart of combat operations costs and the direct economic value of vegetation likely to be affected by fire. The simulation of actual forest fires which occurred in the study period was undertaken using the KITRAL system, which is a mathematical model of fire spread developed specifically for Chile, validated statistically by Castillo (1998), and used in repeated scientific studies (Pedernera & Julio, 1999; Castillo *et al.*, 2014) which confirm the reliability of its calculation. This tool was used to recreate different fires for this research, based on meteorological, topographical and combustible fuel conditions. Thus these results were associated with indicators for area and perimeter, which had previously been used for calculating productivity models.

Methods

Study area

The research considered a geographical area of approximately 112,000 hectares (Figure 1) and identified 5,876 forest fires that occurred between 1998 and 2009. The area further provides a validation sector for the results, by incorporating databases for the years 2010 and 2012. Operational costs for aerial and terrestrial means (expressed in dollars) were sourced from the Chile National Forestry Corporation, the institution responsible for the protection of more than 13.5 million hectares of forests.

In geographical and environmental terms, the study area was situated in an area of high forest fire occurrence with a Mediterranean climate. Similar climates are found in Spain, Portugal, Greece, France and Italy. Human influence has a high impact on initiation and spread of forest fires (Le Houérou, 1987; Leone *et al.*, 2002; Lloret *et al.*, 2002; Koutsias *et al.*, 2005).

Criteria used for extinction efficiency

The first stage in data analysis was to define supply criteria for efficiency model inputs. This was undertaken by considering the economic value of forestry resources, deriving results from the simulation of forest fires in free advance and the extinction costs of actual firefighting activity. Studies with similar characteristics were carried out by Reams *et al.*, 2005 and Mavsar *et al.*, 2013, through the review of strategies for firefighting and decision-making support, with emphasis on wildland urban interface areas. In both studies, economic values were considered in order to determine the level of awareness of the best practices to use to confront fire. In the case of this research, the simulation component was also included to support the economic variable.

b.1. - Economic value of forestry resources. The resources involved in efficiency were consolidated in commercial plantations of radiata pine (the main com-

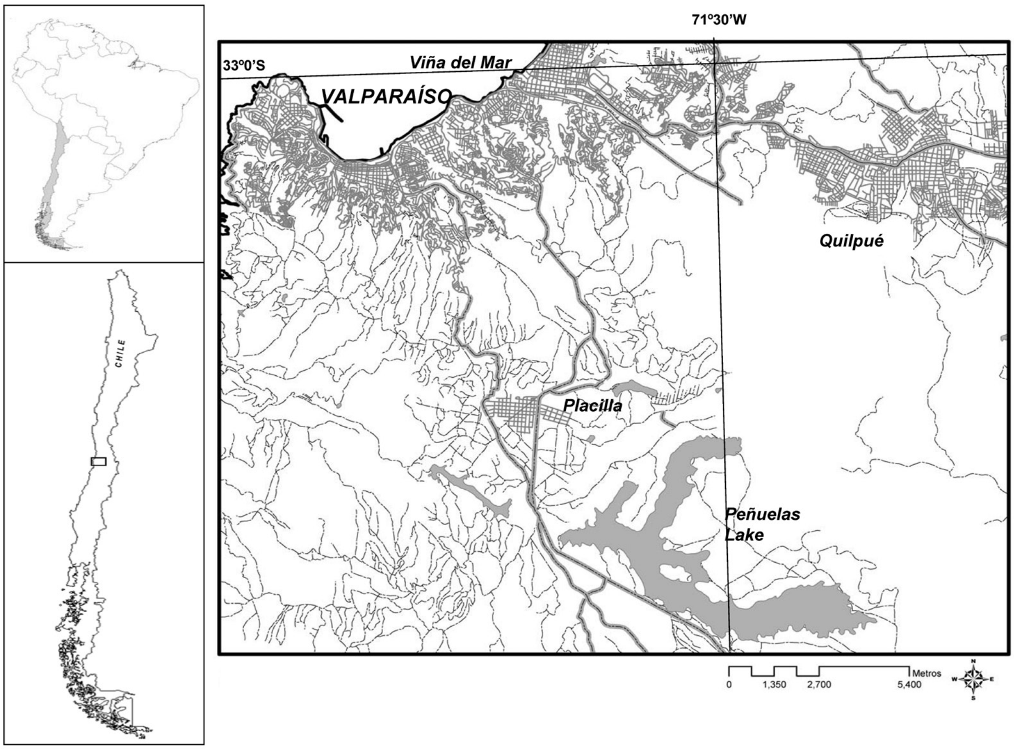

Figure 1. Study area. Valparaíso region, Central Chile.

mercial forestry species in Chile): Parameter *A*; commercial eucalyptus plantations: Parameter *B*; native woodland (all subcategories): Parameter *C*; native scrubland (all subcategories): Parameter *D*, and grasslands with mixtures of scrubland: Parameter *E*. Due to the wide variety of sizes of recorded fires, five categories were defined in terms of number of occurrences. Normally there are more records for fires less than one hectare in size and a smaller number of records for large fires. Table 1 shows a group of records usually applied in forestry statistics for fires in Chile. For this initial analysis, the burnt area is defined with the parameter φ. Thus a new mathematical expression for the economic value of losses ρ, is given for:

$$\rho = \varphi^* \{n, \varphi\} \qquad [1]$$

Here, φ^* represents the variation in surface for each section of spread, depending on the type of fuel affected.

The function determining the burnt area φ was defined for the duration of the fire up until the point when the fire was contained by the perimeter. In this aspect, the analysis categorizes fires according to the size classes presented in Table 1: < 1.00 ha; 1.01-5.00 ha; 5.01-20 ha; 20.01-50.00 ha, and >50.00 ha. Information from the results obtained for these size categories may be integrated with function ρ and used to obtain the value of losses for each of these groups:

As shown in the previous chart, more than 77% of the sample focuses on fires of small surface area. In this respect it is clear that small fires can affect vegetation of the highest commercial value and are responsible for

Table 1. Loss values (stated in US$), for size categories (burnt area in hectares)

Size category (ha)	*N*	%	Average value $\rho = f(n, A, \ldots, E)$ in US$.	*Total (US$)* $\rho = f(n)^*$
≤ 1	4,560	77.76	1,713.24	7,812,374.40
> 1 ≤ 5	915	15.57	15,480.98	14,165,096.70
> 5 ≤ 20	233	3.96	82,281.51	19,171,591.83
> 20 ≤ 50	82	1.40	242,082.75	19,850,785.50
> 50	86	1.47	1,628,442.49	140,046,054.14

* Fires reported for the period 2009-2012.

practically 85% of total damage. The values indicated in Table 1 show the total effect on the vegetation involved in each fire. However, this does not take into account internal variations or proportions of burnt area per vegetation type, because this information was not available in the fire records considered for this study.

b.2. - Analysis of Contraction Factor (FCS)

In order to represent the result from efficiency analysis inputs, it was necessary to determine the expression or effect of the computational simulation of damage using the Chilean KITRAL system, by measuring fires geometrically. For this purpose, a coefficient indicator that measures the relationship between fires in free advance (without containment of extinction activities and simulated in this computer system) and their relationship to fire spread in the presence of firefighting work was defined. Rodríguez y Silva & González-Cabán (2010) studied this relation as an input variable for a decision-making support system called SINAMI. Thus an indicator known as the superficial contraction factor *(FCS)* may therefore be defined as the ratio of actual fire spread against containment activities and free advance (actual/free). Data for fire control actions was obtained directly from fire factsheets or records, as well as the areas recorded at the time of fire perimeter containment.

b.3. - Definition of the extinction costs function

This information was compared in turn with information from the fire simulator, which resulted in the definition of a cost and loss function that depends on affected area and duration of fire spread. This was defined in the following expression:

$$M\,(c + d) = h\,(\mathrm{a}, T) * FCS + d\,(\mathrm{a}, FCS, T) \qquad [2]$$

In the expression above, M is the function that defines the mathematical dependence on the sum of operational extinction costs (c), and economic losses (d). This function varies in relation to affected area (a), superficial contraction factor (FCS) and the duration of the fire (T). Considering that in theory, marginal extinction costs (h) increase with the affected area, the number of fires (N) directly influences the attendance capacity of terrestrial and aerial resources for combat:

$$\frac{\partial M(c+d)}{\partial FCS} = N + \frac{\partial d)}{\partial FCS} = 0.\ \text{Therefore:}\ N = -\frac{\partial d}{\partial FCS} \qquad [3]$$

By incorporating FCS into the analysis, taking account of the affected area now allows the following expression to be obtained:

$$\frac{\partial M(c+d)}{\partial a} = \frac{\partial h}{\partial a} FCS + \left\{ \frac{\partial d}{\partial FCS} * \frac{\partial FCS}{\partial a} \right\} = 0,$$

$$\text{to obtain} \qquad = \frac{\partial h}{\partial a} FCS - N \frac{\partial FCS}{\partial a} = 0 \qquad [4]$$

The point of equilibrium must now be found by developing the FCS and marginal costs of extinction (h):

$$\frac{\partial M(c+d)}{\partial\,(h * FCS)} = 1 + \frac{\partial d}{\partial (h * FCS)} = 0,$$

$$\text{so that} \qquad \frac{\partial d}{\partial (h * FCS)} = -1 \qquad [5]$$

In the expressions above, the critical value to be determined is the average cost identified for each progressive unit of affected area, to facilitate classification into the appropriate category. González-Cabán (2013) uses a similar approach for the qualitative diagnosis of the economic dimension attributed to fires.

Results

Using the data in Table 1, average extinction costs that considered the quantity and type of resources for combat of each fire were obtained. A total of 5,876 fires were processed, which enabled Table 2 to be formulated. These results of economic losses and the simulation of these fires were applied to unit costs by means of KITRAL-adapted electronic spreadsheets.

The next step was the application of expressions [1] of value for economic losses and the function of costs and losses developed in expressions [2] to [5] to represent mathematically the relationship between inputs (costs and combination of extinction methods) and the combination of these expressed in the area and perimeter affected (FCS calculation). Factors were ordered according to the following mathematical expressions:

Affected area (a); Economic losses (plant and forest resources) (φ); Superficial contraction factor (FCS) and extinction costs (C_e). In this instance, the separated expression of the previous variables is as follows:

$$a = A_a * FCS^{\alpha_a} \rightarrow \ln_a = A_a^{*} + \alpha_a * \ln(FCS) \qquad [6]$$

$$\varphi = A_\varphi * a^{\beta_\varphi} * FCS^{\alpha_\varphi} \rightarrow \ln_\varphi = A_\varphi^{*} + \beta_\varphi \ln_a * \alpha_\varphi \ln(FCS)\ [7]$$

$$c_e = A_{c_e} * \varphi^{\theta_{c_e}} * FCS^{\alpha_{c_e}} \rightarrow \ln_{c_e} = A^{*}_{c_e} + \theta_{c_e} \ln_\varphi * \alpha_{c_e} \ln(FCS)\ [8]$$

Table 2. Average costs (expressed in US$), per size category (burnt area in hectares), and related to quantity and type of resources used for fire fighting(*)

Size category (ha)	*n*	%	Average cost/event h(a) US$/ha *	Combination of resources used most	Total associated cost (US$) of the sample
≤ 1	4,560	77.76	3,077.96	2 brigades of 8 fire fighters, 1 helicopter	14,035,497.60
> 1 ≤ 5	915	15.57	4,222.80	4 brigades, 1 fire engine or truck, 1 helicopter	3,863,862.00
> 5 ≤ 20	233	3.96	6,424.07	4 brigades, 1 aeroplane or 1 helicopter	1,496,808.31
> 20 ≤ 50	82	1.40	5,847.88	4 brigades, 2 fire engines or trucks, 2 helicopters, 1 aeroplane	479,526.16
> 50	86	1.47	24,493.05	All available resources	2,106,402.30

* Considers operative costs for aerial and terrestrial resources.

Considering values a and φ, respective calculations for the spreadsheet of 5,876 fires were made using the average of the natural logarithm for each of these parameters, classified into the size categories mentioned previously. Thus the productivity analysis was best represented by the following equations:

–Affected area (in hectares): $a = -3.75 + 2{,}67 * FCS^{-0.66}$ [9]

–Direct losses (in US$): $\varphi = -10.54 + a^{5.03} * FCS^{-0.377}$ [10]

–Extinction costs (in US$): $c_e = 41.02 * \varphi^{0.418} * FCS^{-0.47}$ [11]

As validation for these parameters for the 5,876 fires, an actual occurrence that took place in the study area was used and simulated with KITRAL to calculate the *FCS*. Terrestrial and aerial resources used in firefighting tasks in those flanks or sectors where fire control was prioritized were evaluated. The *FCS* and parameters a, φ and ce were defined. Land, meteorological and actual surrounding vegetation parameters were also defined and used to simulate fire expansion in free advance as well as where defense lines were incorporated. Table 3 was compiled using the results obtained by the KITRAL system (spread of fire each 30 minutes), which illustrates the application of productivity factors.

These results varied considerably for the characteristics of each fire, especially for the *FCS* calculation. In each case, different types of plant fuel and local conditions favoring the spread of fire broaden the admissible ranges of a, φ and Ce considerably. Even though these models are new, they provide a first mathematical approximation to support decision-making regarding the allocation of extinction methods for fire combat, with the advantage that these functions may be applied to other fire scenarios. In order to use these functions to make accurate predictions, it is important to use input data of the optimum quality, quantity and reliability, especially in terms of partial phases of fire advance, combat techniques during fire advance and a detailed record of losses, supported by a fire expansion simulator.

The efficiency analysis may also be addressed in terms of the proportion of vegetation affected by fire. In the past, direct and indirect losses were estimated according to size categories. Generally the highest amount of damage tended to be concentrated in a reduced number of fires. However it is now appropriate to analyze the impacts in terms of fire size categories. In this analysis, data was separated into five groups in order to minimize the mathematical effect of standard deviation of results for de burnt areas from all data considered. Thus the criteria are applied as follows: Example of a fire of size category 1.01 – 5 ha: $Vp = \alpha *$. Loss value of radiata pine + $\beta *$ Eucalyptus loss

Table 3.- Productivity evaluation parameters for extinction tasks (spread of fire each 30 min.)

Actual advance (ha)	KITRAL advance (with defence)	KITRAL advance (free)	*FCS*	*1 – FCS*	a	φ	c_e
4.00	6.03	25.55	0.156	0.844	5.33	9,079.51	4,425.59
5.15	8.05	31.07	0.165	0.835	4.99	6,402.27	3,723.01
6.20	8.71	38.93	0.159	0.841	5.23	8,183.96	4,203.63
6.50	9.34	51	0.127	0.873	6.65	29,891.19	8,021.61

value + γ * Native woodland loss value + δ * Native scrubland loss value + φ * Loss value of grasslands and scrubland mixtures. Results were thus obtained for each size category, expressed in Table 4.

Table 4. Segmentation of direct losses, according to proportion of affected vegetation.

Size category *T*(ha)	**Nº fires**	***Vp* (average) (US$)**
≤ 1	108	847.43
> 1 ≤ 5	45	2,505.69
> 5 ≤ 20	18	3,481.73
> 20 ≤ 50	4	4,389.88
> 50	5	72,861.43

Discussion

In each of the cases mentioned in Table 2, a detailed characterization of the combination of the most-used resources was undertaken. Normally, these combinations can alternate, especially when dealing with fires in interface areas. In these cases, the use of aerial means for rapid containment of fire advance predominates, in areas not usually exceeding one hectare. Linking this information to average response times, it is necessary to establish intervals with a factor called *effective time* that corresponds to a reduction in the calculations generated from each combat phase. According to the references of Rodríguez y Silva & González-Cabán (2010), this value fluctuates by around 0.8. This information was used to create a table of extinction unit (factor *c*), considering the period from the *first attack* phase until the *extinction* of the fire, which for this study comprises those activities which allow the fire advance perimeter to be contained and under effective availability of aerial and terrestrial resources. Post-extinction follow-up times (once the fire advance perimeter has been contained) have been excluded because there were insufficient records to establish costs. The former may be expressed as a simple mathematical ratio, which considers the successive sum of resources *j*, for a combination of the same amongst aerial and terrestrial α, in an operation time threshold *t* for each size category *T*, and at an extinction unit cost C_u:

$$c_\alpha = \sum_{j=1}^{n} j_i \left\{ t_T * c_{u_T} * \alpha_T \right\} \qquad [12]$$

Table 5 shows the costs c_α calculated for each size category *T*:

Table 5. Extinction unit costs (*c*) under fire fighting conditions (α), including effective time factor (*t*) and resource type (*j*) used for each section (*T*)

Size category *T*(ha)	**Combination of most used resources (α)**	**Average operative time (*t*) under condition (α)**	$c_\alpha = \sum_{j=1}^{n} j_i \left\{ t_T * c_{u_T} * \alpha_T \right\}$ **(*) Value in US$**
≤ 1	2 brigades of 8 fire fighters, 1 helicopter	35’ (0.9 hrs.)	2,024.38
> 1 ≤ 5	4 brigades, 1 fire engine or truck, 1 helicopter	117’ (1.95 hrs.)	7,708.27
> 5 ≤ 20	4 brigades, 1 plane or 1 helicopter	557’ (9.29 hrs.)	Range 24,137.77 – 35,584.72
> 20 ≤ 50	4 brigades, 2 fire engines or trucks, 2 helicopters, 1 plane	806’ (13.44 hrs.)	96,173.82
> 50	All available resources	3,175’ (52.92 hrs.)	> 100,000.00

(*) C_u corresponds to cost/hour, for each type of fire fighting unit (aerial and terrestrial).

Surface intervals were considered for economic analysis allow an approximation of the degree of combat efficiency to be established, through the inclusion of the following criteria: extinction (combat) costs, value of unaffected resources and economic value of affected resources. This information may be used to determine technical efficiency which is based on the timely control of the fire advance perimeter and which in turn defines the FCS under local conditions where containment activities are carried out. Rodríguez y Silva & González-Cabán (2012), express this relationship as follows:

$$E_t = 1 - \frac{C_e}{V_{sa} - V_{ca}} \qquad [13]$$

Here, technical efficiency E_t depends essentially on extinction cost (C_e), and on the difference between the monetary value of unaffected resources (V_{sa}) and affected resources (V_{ca}). It should be noted that the calculation considers the direct and indirect value of unaffected resources whilst affected resources are based on the direct damage (commercial losses) segmented by resource type. In this estimation, damage to the interface is not taken into account but should certainly be included in the analysis if more reliable records are available in future. A first approximation of E_t may be established using the calculations based on this equation according to Table 6:

It has been particularly difficult to establish a precise approximation of E_t, because the actual conditions and combat strategies for each fire vary considerably, even within the size categories analyzed here. For example, the study of field operations efficiency located in interface areas requires a more precise evaluation of the intangible environmental assets that are affected and the extinction costs. In the case of E_t estimated for fires under 1 hectare, extremely serious situations usually occur when fire spread seriously compromises interface areas. This often makes it necessary to use a higher allocation of aerial and terrestrial resources than is available at the time –for example, in situations of multiple fire occurrence–; this means that the efficiency factor, even though greater than 66%, is comparatively lower than other categories of fire size. The highest values obtained for categories >1–<=5 y >5–<=20 hectares, may be explained mainly by a closer alignment between the allocation of resources for extinction and extinction costs, when comparing the database for each fire. In the case of fires of a larger size, fire spread has a strong influence and acquires especially conflictive characteristics when fire spread exceeds 25 to 30 minutes. In such cases, extinction efficiency may only be evaluated in those advance fronts where it is possible to measure with precision the comparative effect produced between fire containment as a result of construction of defense lines and aerial actions and free spread.

Conclusions

The comparative analysis of fire spread for fires where there were defense barriers contrasted with the spread of fire in free advance, provides useful references for determining the degree of efficiency in containment works, as well as the potential projection of losses. Thus the application of the superficial contraction factor (*FCS*) demonstrated that it was possible to evaluate with greater precision the differences between both scenarios and thus to better analyze the extinction costs incurred by each of the fires attended.

The economic analysis of input variables and fire combat product for the study area and the subsequent results demonstrate that it is possible to establish links between burnt area, extinction costs and economic losses. Therefore in order for the application of the mathematical models proposed here to have a practical benefit, it is necessary to have a very varied and statistically reliable database, which registers information about as many situations as possible regarding the variables used in the construction of these models. Finally, it should be noted that these first results ob-

Table 6. Technical efficiency in extinction operations, segmented according to fire size category

Size category *T*(ha)	Extinction costs (*)(US$) C_e	Value of unaffected resources (US$) ($V_{sa}$)	Value of affected resources (US$)($V_{ca}$)	Technical efficiency E_t
≤ 1	2,024.38	6,862.47	847.43	0.663
> 1 ≤ 5	7,708.27	52,680.72	2,505.69	0.846
> 5 ≤ 20	29,861.25	160,357.79	3,481.73	0.809
> 20 ≤ 50	96,173.82	391,817.50	4,389.88	0.751
> 50	> 100,000.00	813,084.17	72,861.43	0.594

(*) Expresses a value based on average containment time, according to aerial and terrestrial resources (α), for each size category.

tained for the study area allow more precise records to be used in further research by broadening the sample base of fires of a greater size, in order to corroborate the technical coefficients associated with the productivity equations proposed here and to maintain its degree of reliability.

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