A Model for Dynamic Programming to Back Strategic Planning for Fire Management in Chile[1]

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Abstract

Forest fires in Chile are a very major problem which affects both the environment and forestry work. Although Chile has a highly developed pre-suppression and fire-fighting system, over the last 15 years the effectiveness of our protection systems (measured by the average size of fires) has remained constant, while the budgets directed at protection have grown steadily, in particular in the private sector. The public sector, for its part, has been faced with difficult times, when budget assignation has been hindered by other national priorities and by the major difficulty of providing a foundation for applications for resources with no technical back-up. As a way of resolving this problem, a mathematical programming model was developed which represents the first step towards a planning scheme based on the economic analysis of fire management operations. The model determines the optimal size of the land-based fire-fighting team necessary at regional level, in order to adequately deal with fire problems which may occur within the area which the public sector protection programmes are responsible for.

This model considers the analysis of coverage by land-based fire-fighting units using a cost of access scheme, where a vehicle moves over a surface which provides friction upon displacement. The friction surface is constructed on the basis of the regional road network and average speed of displacement per road-type. A number of locations for the land-based fire-fighting units are also considered as centres providing fire protection. Following this is a dynamic programming model which evaluates the different possible combinations of locations on the basis of the coverage which each location provides to the system, maximizing the surface area under coverage. The model developed is applied to the Forest Fire Protection Programme system operated by the National Forestry Corporation in region 8 in Chile.

Introduction

Over the last 15 years the occurrence of forest fires has remained relatively constant, in spite of the many efforts made to improve the efficiency of fire-fighting operations. Although these efforts have been permanently oriented towards improving resources and the use of airborne material and resources, little or nothing has been done as regards reviewing fire protection design and the strategy which must direct fire management, in both the public and private sector.

In this respect it should be mentioned that budgets directed at forest fire protection have been constantly increased, without any real effect on the decrease in fires, or the affected surface area. This is particularly important in the private sector, where the level of

[1] An abbreviated version of this paper was presented as a poster at the second international symposium on fire economics, planning and policy: a global view, 19–22 April, 2004, Córdoba, Spain.

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expenditure on protection is equivalent to approximately 1.5 times government investment in this area.

For its part, the public sector must compete for resources with other national priorities, so that fire protection system directors must make great efforts to justify the requests for resources to the national authorities.

The aim of this study is to provide a methodological tool to facilitate strategic fire-management planning in the public sector, by defining the right size of fire-fighting force required at regional level, in order to maximize the number of fires which may be attended to in the Bío Bío Region's National Forestry Corporation operating area of the fire management programme.

Materials and Method

This study was run in Chile's region 8 which possesses a major proportion of the natural resources of the major forestry companies and at the same time represents the region with the largest proportion of forest fires nationally over the last five years.

To undertake the study we used digital information on forest fires, the regional road network, and the coordinates of 34 locations which the region uses in the protection programme. This information was provided for the purpose on magnetic support by the National Forestry Corporation.

To handle the data, SPSS v.11 software; the geographical information systems Arcinfo, Arcview and Idrisi; and software developed for applications used for fire management by the University of Chile's Forest Fire Laboratory were all used.

The working method was to undertake three independent and successive analyses: to determine the maximum permissible response time (arrival at fire site) in the region; to calculate the areas of cover for the maximum permissible time calculated in the previous stage; and finally to run an optimising model which would identify and select the combination of locations which would maximize the number of fires which could be attended to in the region. The description of each of these stages is presented in the following pages.

Determination of response time

To determine the response times, data on fires affecting 100 hectares of surface area or less, which had occurred in the Bío Bío region between 1992/93 and 2001/2002 was taken from the data base of the National Forestry Corporation fire management statistics system. Thus, the data base consisted of 24,328 fires which underwent a verification process with the aim or ruling out any inconsistencies. In this process, 4,419 fires with some problem or other were detected and ruled out of the analysis, allowing us to obtain a definitive data base with 19,909 correctly described fires.

In addition, it should be mentioned that amongst the 19,909 fires included in the data base, there were a number of fires which recorded a discrepancy between the date and time of detection and the date and time of the first fire-fighting attack, which was given as 1, 2, 3 or 4 minutes (1,515 records), values which in our view are not sufficiently reliable. Nevertheless, given the absence of other background data, these were included in the analysis, since many of these fires may actually have been spot fires or fires which broke out very close to the position of a fire-fighting team or teams in action.

For each fire in the data base, the difference between the date and time of detection and the date and time of the first attack was calculated, in order to have an estimate of the response time for each fire. For this calculation, the response time was considered to be the time elapsed between detection and commencement of the first fire-fighting action, due to the absence of a data base field which recorded the effective response time for each fire.

This consideration is based on the fact that the dispatch of one or several fire-fighting units is only effective once notification of detection has been received, so that the calculation of the time taken for fire fighters to reach the site of the fire from their bases or stand-by positions only has true significance from the moment at which the unit is dispatched. This action is undertaken only after receiving notification and confirmation of a fire from one of the detection mechanisms used in the protection programme's operations zone.

Later, the response time calculated for each fire was converted into hours and minutes respectively, in order to facilitate later calculations. The working data base was processed using SPSS statistic software in order to obtain the respective descriptive statistics.

In order to study the existence of some direct relationship between affected surface area and response time, a dispersal graph was produced for the two variables, considering the response time as an independent variable and the surface affected as a dependent variable. This graph enables fire grouping levels to be determined, to better define the maximum values for the variables of response time and affected surface area.

Finally, a table of frequencies was constructed with average values for response time and surface area affected, in order to determine the minimum permissible response time, which could then be used in later stages of the study.

Calculation of coverage and determination of the optimal number of land-based fire-fighting units

One of the most important aspects for the success of protection against forest fires has to do with determining the coverage for each one of the operating units in the forest fire protection programme within their area of operations or competence.

In the case of the detection towers, for example, the coverage area is easily determined, as the tower's coverage concerns key protection zones which can be seen directly from the observation point. This surface area may be calculated using digital models of elevations, and tools for calculating visibility levels which are included in most of the Global Information System software.

In the case of land-based resources, a particular difficulty is come across, since the coverage area of these resources depends basically on the transit time from their bases or stand-by positions to the site of the fire they have been assigned to. This transit time depends on several factors (type of vehicle, transit conditions, accessibility to road network and others) which in fact define the time the fire-fighting teams require to reach the site of the fire.

This study used 34 land-based resource locations currently in use by the Bío Bío Region National Forestry Corporation in order to determine the current level of coverage in the region and propose locations which would contribute definitively to maximizing the number of fires which the regional protection system could attend to.

For modelling transit time and calculating coverage we used the access time where a vehicle moves over a surface producing friction on displacement (Eastman, 2000; ESRI, 1993).

This surface was constructed on the basis of the regional road network. Friction on displacement was assigned by average speed of displacement depending on type of road and road surface, following the Ministry of Public Works (MOP, 2000) road manual specifications, presented in *Table 1*.

Type of Road	Design speed (km/hr)	Speed used (Km/Hr)
Urban	60	40
Motorway	115	70
Dual carriageway	95	70
Main roads	95	60
Ring roads	80	40
Local roads	70	30

Table 1*—Speed of displacement used in the study (km/hr).*

The friction or resistance to displacement was assigned to each arc of the road network, diving the length of the arc by the speed at which the vehicle may move, as indicated in table 1.

Displacement across the arcs of the road network was modelled using the SIG Arcinfo network module (ESRI, 1992), using a supply and demand model through a distribution system, in order to identify the sectors which may be reached from each of the stand-by positions within the maximum response time determined in each study.

Movement outside the road network was modelled using SIG Idrisi software (Eastman, 2000), so that it was necessary to use the conversion tools included in the software in order to undertake the change from the vectoral data model (Arcinfo) to the raster data model (Idrisi). The conversion process produced 34 raster files, one for each of the points considered in the evaluation at 25 metre resolution.

The calculation of access time outside the road network was done using a cost of access calculation, based on the maximum ranges calculated for each location using Arcinfo. To do this the Idrisi cost analysis module was used. This takes an algorithm which produces a cost surface area where the distance is measured as the minimum cost (time, effort or expenses) of displacement over the friction surface (Eastman, 2000).

Finally, the coverage areas for each of the 34 locations were obtained using reclassification processes on the respective surfaces of costs produced, for a time equal to the response time determined earlier.

In order to determine the correct number of locations required to be part of the land-based protection system in the Bío Bío region, a dynamic programming model was produced which maximized fire coverage for the region. The model evaluates all possible location combinations, selecting the combination of 1,2,3,….34 points which maximizes overall coverage of the system.

The recursive function produced ed for this case is as follows:

$$C_n = Max \left\{ C_i + C_{n-1} \right\}$$

Where

Cn= is the number of fires covered by a combination of n locations.

Given the strong spatial connotation of the problem under study, the model was implemented to be resolved in a SIG environment, using the GRID module in the SIG Arcinfo software. The model was programmed on a automatic calculation interface, using Arcinfo AML programming language, thus obtaining the combination which maximizes total coverage of the system with each iteration.

Results

Determination of response time

The descriptive statistical analysis of the working data base is shown below in *Table 2.*

Variable	Affected Surface Area (ha)	Time of Arrival (min)
Observations	19,909	19,909
Maximum	100.00	5,125
Minimum	0.01	1.00
Mean	1.51	33.52
Variance	40.46	8,459.57

Table 2*—Descriptive statistics on the working data base*

Table 2 shows that in the case of affected surface area we see a great variability with extreme values of the order of 100 m^2 and a maximum of 100 ha, in accordance with study conditions. The average value observed for this case (1.51 ha) is fairly small, consistent with the variance observed for the population. Nevertheless, in the case of response times, a very high variability is seen in the observations, made evident by the extremely high variance calculated for the population. The same is seen with respect to the extreme values, where the difference between maximum and minimum is 5,124 minutes (85.4 hours).

In order to explore the existence of any relationship between the response time and affected surface are, a figure relating the two variables was produced without processing the information any further. The graph produced is shown below in Figure 1.

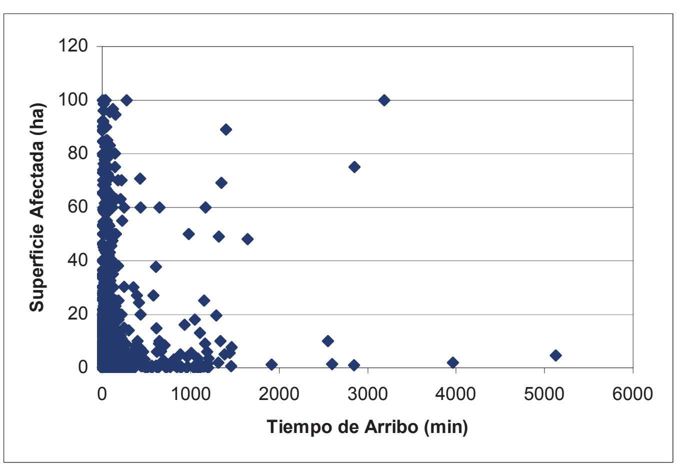

Figure 1—Response times (min) versus Affected Surface Area (ha)

Figure 1 clearly shows the grouping of fires towards categories lower than 1,000 minutes (16.6 hours) response time. Additionally, a high variability as regards surface areas affected can be seen for one same time category.

In order to explore in more detail whether there was any relationship between the data, the same graph was constructed but limiting the range of deployment for response times to values under 100 minutes (1.6 hours), as shown in *Figure 2*.

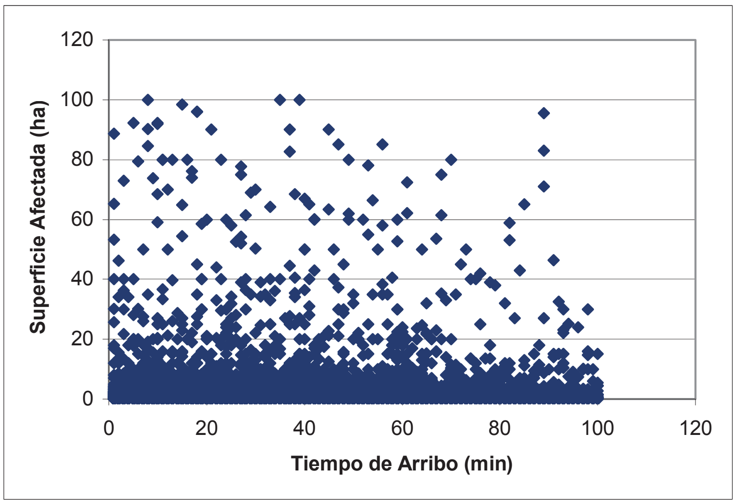

Figure 2—Response times (min) versus Affected Surface Area (ha) for a limited time of 100 minutes

Once again the same effect indicated earlier was observed i.e. for each time of arrival level, a high dispersal of affected surface areas could be seen, with no apparent direct relation between the two variables. This fact became evident on exploring each response time category in the data base, where for each level a high number of different affected surface area values were found.

In addition, when observing *figure 2* in greater detail, it is evident that a high proportion of fires are grouped within levels lower than 20 ha of affected surface area, with broad dispersal of response time values.

After establishing this affected surface area value, which was considered as a limit for improving the level of detail, a frequencies table for each surface area category was drawn up. The categories considered were defined in order to facilitate data analysis by max/min value of detail determined earlier. Thus, fires were grouped into 32 categories, where the first 20 corresponded to categories of one hectare each, and the next categories (12) were defined with variable ranges, up to 100 hectares which was defined as the limit for the study.

For each of these, the number of fires, the mean, and the maximum and minimum values were calculated for affected surface area variables and response time respectively. The usual descriptive statistics were also included for each of the variables considered. *Table 3* shows the results of this process.

Surface area Range (ha)	Number of fires	%	Affected Surface Area (ha)			Time (min.)		
			Maximum	Mean	Minimum	Maximum	Mean	Minimum
0 – 1	15,580	78.26	0.96	0.17	0.01	1,460.00	25.92	1.00
1 – 2	1,772	8.90	1.98	1.29	1.00	2,845.00	45.67	1.00
2 – 3	767	3.85	2.95	2.29	2.00	3,965.00	52.90	1.00
3 – 4	411	2.06	3.91	3.26	3.00	1,201.00	57.52	1.00
4 – 5	266	1.34	4.91	4.24	4.00	5,125.00	79.03	1.00
5 – 6	183	0.92	5.80	5.18	5.00	1,440.00	76.03	1.00
6 – 7	132	0.66	6.95	6.23	6.00	1,186.00	72.92	1.00
7 – 8	86	0.43	7.90	7.14	7.00	1,461.00	77.81	5.00
8 – 9	93	0.47	8.80	8.16	8.00	708.00	56.47	1.00
9 – 10	37	0.19	9.90	9.12	9.00	1,161.00	102.35	4.00
10 – 11	79	0.40	10.80	10.07	10.00	2,553.00	111.65	4.00
11 – 12	17	0.09	11.80	11.19	11.00	222.00	63.88	8.00
12 – 13	39	0.20	12.90	12.11	12.00	208.00	39.18	1.00
13 – 14	15	0.08	13.55	13.21	13.00	1,108.00	127.67	2.00
14 – 15	22	0.11	14.75	14.24	14.00	616.00	90.18	7.00
15 – 16	40	0.20	15.90	15.12	15.00	251.00	51.25	2.00
16 – 17	11	0.06	16.90	16.19	16.00	931.00	113.55	1.00
17 – 18	11	0.06	17.97	17.31	17.00	130.00	45.82	4.00
18 – 19	23	0.12	18.20	18.01	18.00	1,050.00	105.30	1.00
19 – 20	3	0.02	19.60	19.27	19.00	1,288.00	437.67	8.00
20 – 25	76	0.38	24.75	21.16	20.00	432.00	60.95	3.00
25 – 30	42	0.21	29.60	26.23	25.00	1,150.00	92.64	1.00
30 – 35	33	0.17	34.30	31.35	30.00	355.00	57.48	1.00
35 – 40	29	0.15	39.65	36.50	35.00	607.00	75.48	3.00
40 – 45	21	0.11	44.50	40.85	40.00	104.00	41.10	1.00
45 – 50	9	0.05	49.00	46.40	45.00	1,642.00	379.11	2.00
50 – 60	29	0.15	59.10	52.71	50.00	980.00	90.79	1.00
60 – 70	31	0.16	69.00	62.88	60.00	1,351.00	171.84	1.00
70 – 80	18	0.09	79.50	73.68	70.00	2,852.00	235.61	3.00
80 – 90	16	0.08	89.00	82.37	80.00	1,403.00	130.25	1.00
90 – 100	13	0.07	98.50	93.37	90.00	153.00	42.23	5.00
Over 100	5	0.03	100.00	100.00	100.00	3,186.00	709.00	8.00
Total	19,909	100	923.33	861.31	835.01	43,124.00	3,919.25	85.00
Mean	622.16		28.85	26.92	26.09	1,347.63	122.48	2.66
Maximum	15,580	0.78	100.00	100.00	100.00	5,125.00	709.00	8.00
Minimum	3.00	0.03	0.96	0.17	0.01	104.00	25.92	1.00
Variance	7,561,608.91		869.26	783.63	740.52	1,377,479.92	19,681.00	5.46
Deviation	2,749.84		29.48	27.99	27.21	1,173.66	140.29	2.34

Table 3*—Grouping and ordering of data into 32 categories of Affected Surface Area*

From *Table 3* it can be seen that around 90% of fires show an affected surface area of under 5 ha, with response times under 60 minutes (one hour). Moreover, almost 80% of total fires are concentrated within category one (less than one hectare of affected surface area) and the mean value for response time for that category is of the order of 26 minutes (25,92 min.).

It is clear that there is very high variability with regard to response times, an effect which occurs due to the dispersal of the affected surface area for the same minute of response time. This would lead one to think that there is no direct relation between these two variables. We can be sure of this, given that the final surface area affected by a forest fire depends on other factors (fuels, environmental conditions, topography, fire-fighting action) which conditions the behaviour of the fire, and consequently the propagation model and final surface area affected by fire.

However, to resolve the response time a graph was constructed which shows the surface area affected and the response times for each of the 32 categories of fire size defined in this analysis.

The data was ordered by size category and affected surface area and response times were plotted on a graph independently, with the same scale of values on the *Y* axis, in order to observe the behaviour of the two variables simultaneously. The result of this process can be seen below in *Figure 3*.

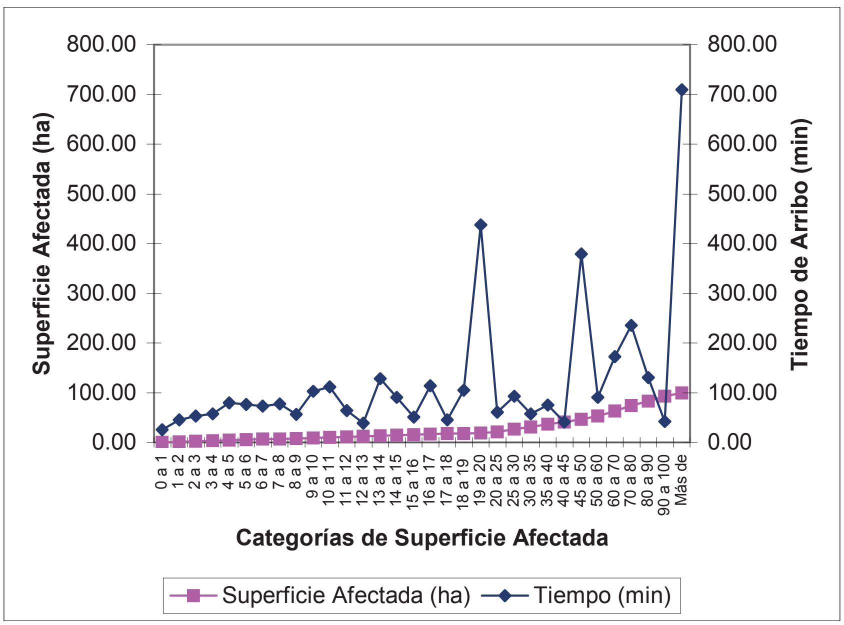

Figure 3—Distribution of the Mean Surface Area Affected and Mean Response time for 32 size categories of forest fire

In *Figure 3* one can clearly see the exponential trend shown by the affected surface area: the longer the time taken to initiate the first fire-fighting action, the greater the final surface area affected. The trend in this case shows a quadratic or exponential curve which makes the analysis consistent with the findings of Julio[3] (1999), in that the difficulty of controlling a fire (and consequently the affected surface area) increases in exponential terms with regard to the time elapsed, or delay, before initiating control.

Another interesting aspect has to do with the way in which the increase in response time (time of arrival at the site of the fire) is shown. This shows variations with no defined behaviour. In any case it is well known that as the time of arrival at the fire increases, the affected surface area also increases. In this case one cannot find a clear trend, given the high variability seen in the data.

Given the form of the curves and the frequency values calculated for each fire size category (*Table 3*), it can be concluded that "optimal" response time is in the first size category (0 to 1 hectares affected) where, on average, the fire-fighting units took 26 minutes to initiate the first attack. Coincidentally this category also groups together the major proportion (78.26 percent) of the fires recorded in the data base (*Table 3*).

Calculation of coverage and determination of the optimal number of land-based combat units

By applying algorithms to calculate routes and costs of access in the SIG environment, 34 coverage maps were produced for locations included in the analysis. Figure 4 shows an example of the result of the calculation obtained using SIG Idrisi.

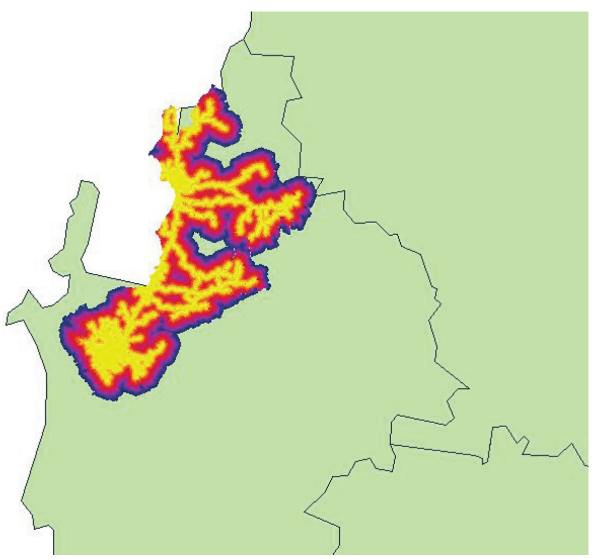

Figure 4—Costs of access for location of brigade 301. The colour bands represent the time (in minutes) taken by a vehicle to reach a pixel, up to a maximum of 26 minutes.

[3] Julio Guillermo, Basics of Fire Management, Manual of Forestry Engineering, Faculty of Forestry Sciences, University of Chile.

Figure 4 clearly shows the influence of the road network over the surface area the fire-fighting unit is able to reach within the maximum response time determined in this study.

The 34 coverage maps were subjected to a process of raster superimposition with the image corresponding to the occurrence of forest fires in the region, in order to obtain an estimate of the historical mean potential work load for each unit. The result of this process can be seen in Table 4.

Location	No. of Fires	Location	No. of Fires
1	590.4	18	170.2
2	499.8	19	372.8
3	666.0	20	264.4
4	845.8	21	385.4
5	792.8	22	276.2
6	787.8	23	290.6
7	806.6	24	442.4
8	803.2	25	250.2
9	822.0	26	445.4
10	845.8	27	255.0
11	268.2	28	882.2
12	205.6	29	1082.0
13	265.0	30	600.0
14	264.4	31	1081.0
15	287.8	32	109.2
16	329.6	33	107.4
17	290.6	34	104.4

Table 4*—Average number of fires (seasons1992/93 to 2001/02) within coverage by each of the 34 locations evaluated.*

As was expected, on superimposing the fire-fighting units' coverage areas with the occurrence of regional fires, different values were obtained for each of the locations. In this case, location number 29 stands out as the one which contributes the greatest number of fires to the total coverage of the system. This is not surprising, given that this location is in an area which historically has registered the highest number of fires in the region, the reason for which this unit is the one with the heaviest potential workload in the region. The same occurs in location 31 which is within the same zone where occurrence is concentrated.

The locations which make least contribution to the system are 33 and 34. These may have been incorrectly selected and should perhaps be removed from the system.

Using the SIG tools used in the study, an overall coverage map was constructed for all locations currently in use by the National Forestry Corporation in the Bío Bío region. This map is presented below, in Figure 5.

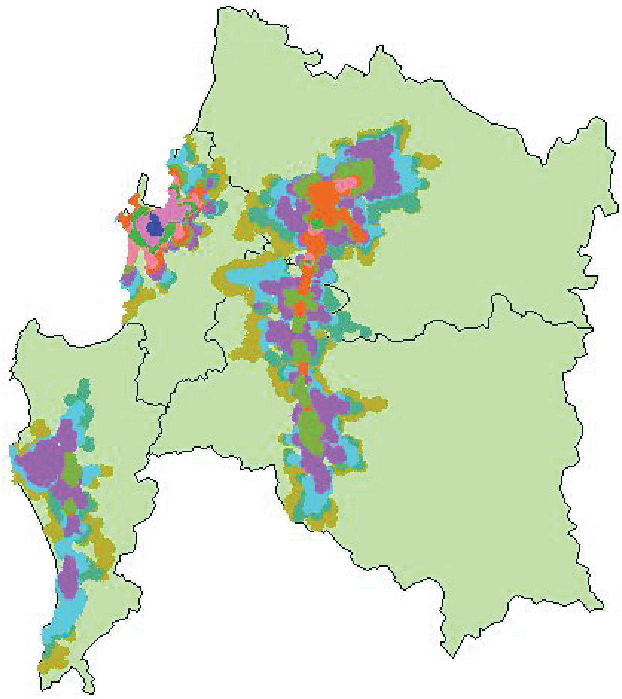

Figure 5—Current coverage of the land-based units in the Bío Bío region. The colour bands represent the amount of units which cover the same points (blue 10 units, green 1 unit)

Current coverage of the region's protection system is located more in the area close to the city of Concepción, the central valley, and the south-western area of the region, sectors which traditionally have the highest concentration of regional fires. Another interesting aspect to mention is the existence of sectors which show a level of over protection in the sense that they are covered by up to 10 different fire-fighting units at the same time.

The use of the dynamic programming model resolved the coverage problem, determining a combination which, in a first stage, maintains the same level of current cover (in terms of surface area) with fewer locations included in the system. Table 5 shows the final summary of applying the model developed for this study. This table shows the historical mean maximum number of fires covered by the protection system for each combination.

N	No. of Fires	N	No. of Fires
1	1082.0	18	3714.4
2	1992.6	19	3720.4
3	1938.4	20	3725.2
4	2383.8	21	3729.6
5	2724.6	22	3733.4
6	3048.2	23	3735.6
7	3277.2	24	3736.4
8	3384.6	25	3737.0
9	3451.6	26	3737.6
10	3508.0	27	3738.0
11	3555.6	28	3738.0
12	3587.6	29	3738.0
13	3617.6	30	3738.0
14	3647.0	31	3738.0
15	3675.8	32	3738.0
16	3691.2	33	3738.0
17	3699.2	34	3738.0

Table 5*—Mean number of fires covered by the best combination of n locations.*

From the background data in the table it can be seen that in the first iterations, the coverage contribution rises rapidly to establish itself after 27 locations. This trend may be seen more easily in Figure 6.

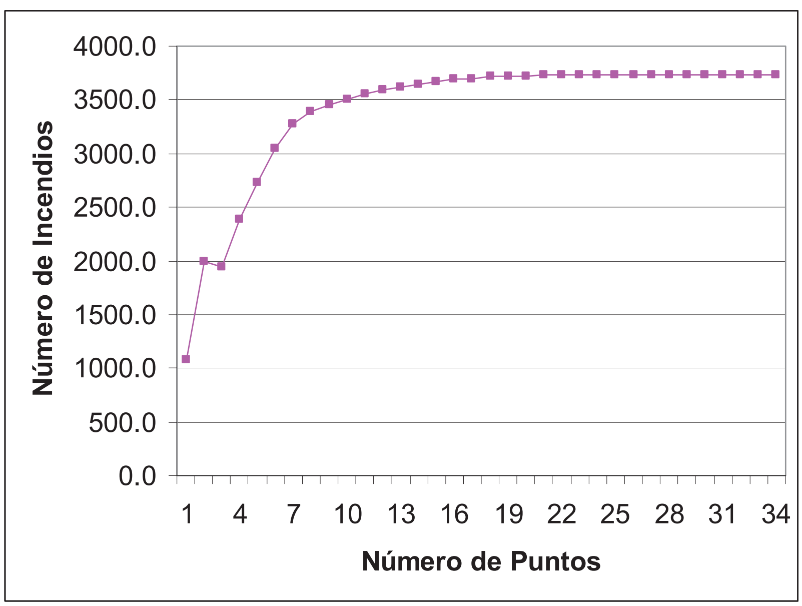

Figure 6—Evolution of the number of fires within coverage, for the best combination of locations.

The figure clearly shows the trend towards stabilization for the coverage level from 26 locations upwards, giving the maximum number of possible fires attended by the resources provided by the region for forest fire-fighting. This combination, which maximizes coverage, corresponds to the points 29, 30, 4, 26, 6, 16, 13, 33, 27, 2, 25, 19, 17, 5, 15, 14, 18, 32, 28, 9, 24, 8, 21, 7, 20 and 22.

Conclusions

The model developed made it possible to determine the optimal number of locations which must be considered in strategic planning for forest fire protection in the Bío Bío region.

Calculation procedures for coverage areas proved to be efficient in estimating the surface area each location considered was responsible for. Nevertheless, it is especially important to consider that speeds of displacement used in this study correspond to the best possible estimate, given the absence of reliable background data on displacement speeds of vehicles in different conditions of road surface.

As a result of the background data provided by this study, the National Forestry Corporation has a new tool to justify the amount of fire-fighting units which should be used in the region in order to ensure an adequate level of protection.

Finally, it is necessary to continue running studies along these lines in order to implement an economic analysis tool for fire management in the public sector in Chile.

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