Economic Analysis of Risk and Choice under Uncertainty in Landscape Planning in Relation to Wildfires[1]

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Abstract

Economic decision-making in wildfire defense and fire management programs is not easy when performed under efficiency criteria. The determination of variables to be considered and the lack of data analyzed in relation to the results achieved by the action plans adopted to reduce the impact of fires condition the adoption of strategic solutions, both in the management of the landscape against fires and in suppression operations. If, by itself, the decision on how much, where and how to invest protection budgets is complex, the choice in environments of risk and uncertainty undoubtedly increases the difficulty in finding the right solutions.

Determining the expected utility function and measuring risk aversion provide interesting and advanced diagnostic tools that allow comparing the responses that can be provided by the application of different action plans in the forest landscape. Based on the results obtained, the best solution under uncertainty scenarios can be selected. The integration of variables that identify the initial extinction difficulty of the landscape under study, as well as the potential danger of wildfires and their effects on the net change in the value of resources due to the fire's impact and the extinction costs, help characterize the behavior of the expected utility functions. This paper analyzes the results of different utility functions and compares them with the purpose of identifying the expected utility function with the best explanatory capacity when choosing among different fire protection options under situations of uncertainty generated by climate change, the probability of occurrence, and the influence of social behaviors, as well as the different extinction capacities, among other factors. The management of forest fuels and the different opportunities for extinction depending on the combinations of means of suppression can be treated from the approach of choosing strategic solutions in scenarios of uncertainty. The SINAMI (Rodríguez y Silva, González-Cabán, 2010) and Visual-SEVEIF (Rodríguez y Silva, et al. 2013, 2014) models provide the baseline

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data for decision-making and choice of solutions under conditions of uncertainty in the forest landscape.

Keywords: Operational plans, resources net-value change, suppression, suppression costs

Introduction

The fire suppression actions within the framework of landscape fire management programs have changed over time. Scientific advancements in the spatial dynamics of fire propagation in forest lands and better understanding of the fire severity consequences, economic and ecological damages and environmental services have made possible to progressively accommodate fire suppression actions to the knowledge gained and experiences learned.

However, at the same time the complexity of forest scenarios have been modified more or less over the last 50 years depending on the fire incidence in different countries. On one hand, demographic and socioeconomic changes, and on the other hand, the complex accumulation of biomass in conditions ready to ignite and propagate due to severe meteorological conditions are generating new forest landscapes and mix forest-urban landscapes in which the traditional fire suppression programs cannot provide and effective and secure response.

Within this reality decision making becomes uncertain and complex (Mina et al. 2012). In addition, the important budget requirements to administer fire suppression resources incorporates variables and factors difficulting even more development efficient suppression actions (Rodríguez y Silva and González-Cabán. 2016). Uncertainty is a conditioning factor when selecting an ideal solution in decision making, particularly when making strategic changes to improve the fuels distribution over the landscape and in management of an emergency given an action plan.

Finding a solution to the problem at hand (for example, finding the right combination of firefighting resources, number and type, for a specific fire suppression action) usually generates characteristics associate with a more or less risk averse postures. Sometimes, a high risk solution may lead to a highly efficient result, but the uncertainty of what may happen and how the relevant variables would affect or condition the selected option reduces the probability of selecting such option to the emergency.

On the other hand, the selection of solutions in an uncertainty environment (as characteristic of fire suppression actions) frequently are separate from decision models based on economic and results optimization prediction assumptions. This is due in part to the lack of knowledge of these disciplines, and also conditioned by the paucity of models developed for and available for wildland fire management providing solutions considering uncertainty. The selection of solutions continues to be anchored in the actor's empirical experience.

In this work we present a line of inquiry to finding modeled solutions based on economic efficiency principles to generate tools and conceptual contributions that while reducing uncertainty, progressively provide a catalogue of solutions increasing the efficiency and reducing costs of fire management and fire suppression actions (Rodríguez y Silva, and González-Cabán, 2016).

Material and methods

Uncertainty is present in the majority of selections to be made, not only in development of, but in the execution of fire management programs. For example, the selection of the number and type of helicopters based on fire line production capability given different fire behavior scenarios, presence of turbulence and erratic winds on the fire front or the final results of a specific fire suppression action to stop fire progression on a determined sector. In addition, behind the decisions there are also economic criterion, given the decisions that can be adopted with consequences for generating extraordinary expenses and increasing costs.

Therefore, the objective of modeling decision support algorithms should be to reduce, as much as is possible, uncertainty (Minas et al. 2012); by generating a work environment in which the variability of parameters affecting decision making and solutions are qualified by the information explaining the uncertainty framework.

Using experiences from the "choice selection under uncertainty theory" (Gollier 1999), can lead to solutions by the definition and individual valuation of uncertainty. This imply achieving a high scenario knowledge in which the decision to make varies with the decision makers greater or lower willingness to expose themselves to the level of risk and its consequences.

In this work the methodology used correspond to a process integrating thematic blocks that allows to understand through their interconnections the assumptions facilitating the uncertainty reduction in the selection of strategic solutions (Figure 1).

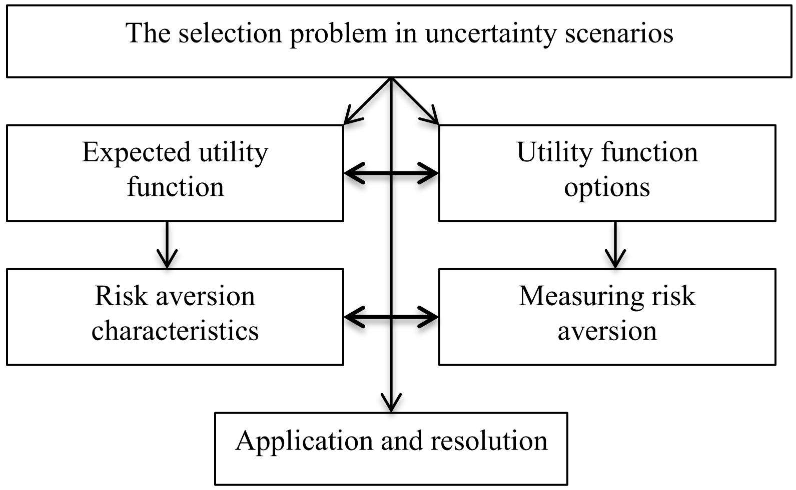

Figure 1. Integration of thematic blocks that facilitates uncertainty reduction in the selection of strategic solutions.

1. **Expected utility function**

In uncertainty scenarios the selection possibility by decision makers is conditioned by factors unbeknown to decision makers themselves. The "state of nature" represents a group of uncertainty scenarios in which the actors do not have concrete factors of control (Variant 2005). On the other hand, it is important to indicate that, conceptually, the influences or effect of positive (benefits) or negative (deterioration and impacts) characteristics depend on actor's preferential criterions and of how they can influence the results.

One state of nature can be defined as the description of a determined uncertainty result. Representing (E) as the set of all possible states of nature and (e) as a finite element of the total possible states, then the probability of that state to occur is given by p(e), and by definition must comply with following conditions:

a) $P(e) \geq 0$
b) $\Sigma_{e \in E} p(e) = 1$

As defined, the solution goes through the contingent plan construction and determination. The contingent plan means the consumption plan representing a concrete specification of the number of units to consume in each of the states of nature. That is, the consumption contingent plan can be defined as a random variable which takes a response value with a specific probability.

If we understand a specific strategic decision in terms of fire suppression or fire management in the ordering of forest fuels as a consumption action from one basket of available goods (strategic opportunities for actions), and at the same time that the consumption option behaves as a random variable (c) then, subject to the comparative preferences conditions, we can determine the expected utility of being able to develop the selected contingent plan.

Mathematically, the definition can be identified by the following expression: $E[U(c)]=\Sigma p(e)U(c))$. Given this relationship, and knowing the different consumption contingent plans or stated differently; different options of fire suppression operational plans or different strategic combinations of firefighting resources in the same operational plan (Castillo and Rodríguez y Silva 2015), it is possible to compare two operational plans in terms of the expected utility each plan can provide: $E[U(c_1)]> E[U(c_2)]$. In some instances, the "consumption contingent plan" can be considered as a "certainty plan", thus the uncertainty scenario becomes a certainty scenario. That is, the number of consumption units in the different states of nature is invariant, thus the expected utility of the different strategic options is the same

To clarify these concepts, as an example, below we present two contingent plans (c_1) and (c_2) in terms of their suppression capabilities, duration of their interventions, and suppression costs (Tables 1 and 2).

Table 1. Contingent plan C_1

Nº of units Contingent Plan C1	Firefighting resource type	Unit productivity (m/min)	Hourly fire suppression costs (€)	Total intervention time in minutes	Total suppression costs (€)	Effectiveness weighting factor	Suppression capability (m/min)
3	Airplane CL215T	85	4,571.92	826	188,820.27	0.143	36.53
3	Helicopter Bell412	55	1,828.57	456	41,691.35	0.079	13.05
3	Helicopter KAMOV K32	75	2,101.09	350	36,769.06	0.061	13.66
4	airplane Air Tractor 802	65	652.99	458	19,937.98	0.079	20.65
10	Hand crew (15 person)	8.5	551.00	1,670	153,362.19	0.290	24.62
1	Bulldozer	35	73.29	256	312.71	0.044	1.55
4	Cistern tank	15	94.01	1,750	10,967.53	0.304	18.21
Operational index C1	15.82			5,766	451,861.09		128.27

Table 2. Contingent Plan C_2

Nº of units contingent Plan C2	Firefighting resource type	Unit productivity (m/min)	Hourly fire suppression costs (€)	Total intervention time in minutes	Total suppression costs (€)	Effectiveness weighting factor	Suppression capability (m/min)
4	Airplane CL215T	85	4,571.92	950	289,554.89	0.1746	59.38
4	HelicopterBell 412	55	1,828.57	321	39,131.35	0.0590	12.98
4	Helicopter KAMOV K32	75	2,101.09	185	25,913.43	0.0340	10.20
2	Airplane Air Tractor 802	65	652.99	750	16,324.76	0.1379	17.92
10	Hand crew (15 person)	8.5	551.00	934	85,772.63	0.1717	14.59
2	Bulldozer	35	73.29	450	1,099.37	0.0827	5.79
5	Cistern truck	15	94.01	1,850	14,492.81	0.3401	25.51
Operational index C2	16.54			5,440	472,289.25		146.37

As seen in the tables, because of different types and combination of firefighting resources selected for each options c_1 and c_2 results show interesting differences for the two contingent plans. Though option c_2 is more expensive, have a higher productivity capability and thus the fire is suppressed faster. However, though option c_1 has lower suppression costs, it also has lower productivity capability and thus the fire takes longer to suppress. This can be seen by looking at the operational index value for contingent plan c_1, which is 15.82 units and for contingent plan c_2, which is 16.54 units. Meaning that contingent plan c_2 is more effective in suppressing the fire. The operational index was computed as follows: $Iop_i=10^{-4}\cdot[0.35\cdot(\text{Total suppression costs})_i + 0.65\cdot(\text{Suppression capability})_i]$.

Taken as random variables c_i, these consumption options or contingent plans imbedded in the utility function defined in the fire management protection plan or fire management plan, allows us to determine their utility as seem the final results obtained. For example, these results can be measured in terms of efficiency or their benefit cost relationship. While selecting the utility function to help us determine the results for comparing the different contingent plans we must consider the economic value of saving the market and nonmarket goods and services affected by forest fires, by interrelating it mathematically with the consumption value of each solution combining the firefighting resources.

2. **Measuring risk aversion**

The decision to select a contingent plan (operational suppression plan) among several considered incorporates an important component of the decision maker attitude towards risk. To better explain this we must conceptualize what is known as an "actuarially just game." This is defined as that game or lottery with an expected value equal to zero. Considering (p) as a probability with values between (0) and (1), then $px + (1-p)y = 0$.

Starting with this concept we can then define a decision maker posture towards risk (Arrow 1965):

a) Risk Averse. A decision maker is risk averse when is not willing to accept any actuarially just game. This can be explained by looking at an individual initial wealth M_0, with x and y as possible gains (increase in wealth) and according to its respective probabilities (p) and (1-p); with U equals to the individual's utility function. Then:
$U(M_0)>p\cdot U(M_0+x)+(1-p)U(M_0+y)$
$U(M_0)=U(p\cdot(M_0+x)+(1-p)\cdot(M_0+y))> p\cdot U(M_0+x)+(1-p)\cdot U(M_0+y)$
Which is a strictly concave function.

b) Risk neutral. A decision maker is risk neutral when it is indifferent to any actuarially just game. Mathematically this can be expressed as:
$U(M_0)=U(p\cdot(M_0+x)+(1-p)\cdot(M_0+y))= p\cdot U(M_0+x)+(1-p)\cdot U(M_0+y)$
Which is a lineal function.

c) Risk taker. A decision maker is risk taker when it is willing to accept any actuarially just game. Mathematically this can be expressed as:
$U(M_0)=U(p\cdot(M_0+x)+(1-p)\cdot(M_0+y))<p\cdot U(M_0+x)+(1-p\cdot U(M_0+y)$
Which is a strictly convex function.

The measurement of a decision maker risk aversion depends more or less on the concavity of the decision maker utility function (Pratt 1964). The absolute curvature value of a utility function is given by ($-U''$). That is, the second derivative of the utility function provides information on the degree of the function concavity; the greater the function concavity the greater is the decision maker risk aversion. Normalizing the second derivate with respect to the first derivative of the utility function we obtain a measurement of risk aversion invariant to related transformations (Arrow 1964, Pratt 1965). The following expression represents the coefficient of the absolute aversion measurement: $R_a(M)= -[U''(M)/U'(M)]$. To measure the aversion in proportion to the starting wealth we use the relative aversion measurement expressed as: $R_r(M)= -[U''(M)/U'(M)]\cdot M$.

The following variables have been considered in determining the consumption function:

- The per hectare value (V_R) of natural resources (market and nonmarket) present in the area where the contingent plans (operational plans defined by their combination of firefighting resources) would be compared.

- The potential per hectare losses (P_R) as a function of fire behavior (depreciation matrix of affected resources values) (Rodríguez y Silva and González-Cabán 2010, Molina et al. 2009, Rodríguez y Silva et al. 2014).
- The operational capacity index (Iop) obtained from the interrelation of firefighting resources type, the unit costs, the intervention times, and the resulting operational capacity (fireline control).

Combining these variables in the consumption function we obtain the "wealth" concept from the considered contingent plan. This new variable becomes the independent or explanatory variable of the utility function in the analysis of the decision maker risk aversion.

Mathematically, the consumption function is given by::

$$C=\frac{(VR-PR)}{Iop}$$

The selected utility function for analyzing aversion is U=ln(C); this function behavior in relation to the Arrow-Pratt criterion is as follow:

1. Absolute Risk Aversion (ARA):

$$ARA=-\frac{U''}{U'}=-\frac{\frac{-1}{C^2}}{\frac{1}{C}}=\frac{1}{C}>0,\ Risk\ Aversion$$

The ARA is decreasing with respect to consumption (C); in effect, the differential ARA with respect to an infinitesimal change in consumption is strictly decreasing:

$$\frac{dAAR}{dc}=-\frac{1}{c^2}<0, Absolute\ Risk\ Aversion\ is\ decreasing\ with\ consumption$$

2. Relative Risk Aversion (RRA):

$$\text{ARR}=c\cdot AAR=c\cdot\frac{1}{c}=1, Constant\ Relative\ Risk\ Aversion$$

We can use the expected utility function to determine the decision maker risk posture. To do this first we need to determine the expected utility value and make a comparison with the expected value. To perform this operation we need to assign the probability (p) that we think makes the decision maker to select

contingent plan C_1, and probability (1-p) corresponding to contingent plan C_2.
As explained before the computational procedure is as follows:
Phase a), determining the expected value:

$$V(C_1, C_2) = p \cdot C_1 + (1 - p) \cdot C_2$$

Phase b), determining expected value utility:

$$U\big(V(C_1, C_2)\big) = \ln(V(C_1, C_2)$$

Phase c), determining expected utility:

$$U(C_1, C_2) = p \cdot Ln(C_1) - (1 - p) \cdot Ln(C_2)$$

Making the comparison to:

$U(M_0)=U(p\cdot(M_0+x)+(1-p)\cdot(M_0+y))> p\cdot U(M_0+x)+(1-p)\cdot U(M_0+y)$,

confirms the existence of a strictly concave functions making the decision maker risk averse.

Application of this procedure to the landscape scenario were the fire takes place we can evaluated the decision maker risk posture with regard to selection of a contingent plan.

There are other consumption utility functions that can be considered similarly to the selection presented in this work. Among the family of utility functions we could consider the following (Gollier 1999), (Table 3):

Table 3. Comparison between utility functions depending on the consumption value (c).

Utility function U(c)	Mathematical formula	Absolute risk aversion	Relative risk aversion	Considerations
Quadratic	$U(c) = c - \frac{b}{2}c^2$ $con\ b > 0$	$Ra(c)) = \frac{1}{1-bc}$	$Rr(c)) = \frac{b^2}{(1-bc)^2}$	Treatment as an inferior good (the greater the (c) value, greater the absolute risk aversion in selecting a contingent plan). Conservative strategy
CARA (Constant absolute risk aversion function)	$U(c) = -\frac{1}{\gamma}e^{-\gamma c}$ con γ>0	$Ra(c) = \gamma$	$Rr(c) = \gamma c$	When relative risk aversion is increasing with the consumption the model provides a direct proportion with consumption.
CRRA (Constant relative risk aversion function)	$U(c) = \frac{c^{1-\sigma} - 1}{1-\sigma}$ con σ≥0 When σ➔1, then $U(c)) = Lnc$	$Ra(c) = \frac{\sigma}{c}$	$Rr(c) = c\frac{\sigma}{c} = \sigma$	When the absolute risk aversion is decreasing with consumption the model predict a predisposition to select the contingent plan with higher consumption.

In relation to its applicability in evaluating contingent plans under uncertainty environments, the study of different utility functions behavior provides an important tool in the comparative strategic analysis of operational suppression plans. The results provide the possibility of creating a book of standardize and eligible solutions according to identified forest landscape uncertainty scenarios to protect from forest fires.

Results

The model application requires setting specific territorial characteristics where the working scenario is defined. Accordingly, as an example, we have considered a $2km^2$ pixel. The economic valuation of the natural resources (market and nonmarket) within the pixel showed a value of 2,425€/ha. Calculation of the economic value of damages caused by a forest fire are analyzed under two aspects. Those defined by the operational results of contingent plans (C_1) y (C_2). The contingent plan (C_1) suppression capability is smaller than that for contingent plan (C_2), its suppression costs are also less, but the total suppression time is larger.

On the other hand, the results from studying the fire occurrence danger index points towards the probability of high velocity drying winds in the 15% range, as compared to a more benign less dangerous situation and therefore, less operationally conflictive, characterized by higher intensity, but also high humidity winds with a 85% probability.

In addition to higher suppression costs and higher suppression capability, selection of contingent plan (C_2), represent differences in the final total fire area affected. By selecting contingent plan (C_2) the total fire area affected is reduced by 15%, though suppression costs increased by 4.3%.

Another important factor is the computation of natural resource NVC after a fire. This value can be estimated using the SEVEIF methodology (Molina et al. 2009, Rodríguez y Silva 2014). Computation of the pre- and post-fire resources economic value allows to determine the saved values. Integrating the saved values information with the operational index (Iop) for the selected contingent plan through its consumption function gives us the "wealth" value in terms of the fire impact economic value saved.

Table 4 shows the results for the selection between the contingent plans given the risk under uncertainty scenarios for the analysis presented in this work.

Table 4. NVC values for each contingent plan and meteorological scenario

Meteorological scenarios	Occurrence probability (%)	NVC/Plan C_1 (€/ha)	NVC/Plan C_2 (€/ha)
EM_1	15	2,425-850=1,575	2,425-550 = 1,875
EM_2	85	2,425-650=1,775	2,425-450 = 1,975

The consumption function values allows us to determine the comparative "wealth" derived from the contingent plans considered. These values are the explanatory variable of the utility function selected for the decision maker risk aversion analysis. In determining the corresponding "wealth" values is necessary to consider the results from each operational index (I_{op}), and apply the consumption function to every resource NVC value resulting from the selected contingent plan and existing meteorological scenarios (Table 5).

Table 5. Consumption function values by contingent plan, meteorological scenarios and operational index

Contingent plan	I_{op}	Meteorological scenarios	NVC (€/ha)	Consumption function values (€/ha)
C_1	15.82	EM_1	1,575	99.55
	15.82	EM_2	1,775	112.19
C_2	16.54	EM_1	1,875	113.36
	16.54	EM_2	1,975	119.40

From these results we can analyze the decision maker decision considering the expected value and expected utility given the consumption function values for each contingent plan available and each meteorological scenarios. Following are two possible solutions decision maker can select:

A)

- Select a fixed solution given by contingent plan C_1 and consumption function value of 112.19 €/ha.
- Select a dynamic solution with a 35% probability of reaching a consumption function value of 99.95 €/ha by selecting contingent plan C_1, and 65% probability of reaching a consumption function value of 119.40 €/ha by selecting contingent plan C_2.

A.1. Fixed expected value

VE(fixed solution) = 0.35 x 112.19 + 0.65 x 112.19 = 112.19 €/ha

A.2. Dynamic expected value

VE(dynamic solution) = 0.35 x 99.95 + 0.65 x 119.40 = 112.59 €/ha

B.1. Fixed expected utility

UE(fixed solution) = 0.35 x Ln(112.19) + 0.65 x Ln(112.19) = 0.15 x 4.72 + 0.85 x 4.72 = 4.72 €/ha

B.2. Dynamic expected utility

UE(dynamic solution) = 0.35 x Ln(99.55) + 0.65 x Ln(119.40) = 0.15 x 4.6 + 0.85 x 4.78 = 4.71 €/ha

Because the expected utility value for the fixed solution is greater than the expected utility value for the dynamic solution (UE(fixed solution) > UE(dynamic solution) the decision maker risk posture is determined by the expected utility and not the expected value. Therefore, we should use the expected utility when evaluating what decision the decision maker will take under conditions of uncertainty.

The error probability of the decision maker being indifferent between the two options (fixed or dynamic solution) is given by the following equation:

0.35 x Ln(112.19) + 0.65 x Ln(112.19) = 0.15 x 4,.72 + 0.85 x 4.72p´x Ln(99.55) + (1-p´) x Ln(119.40) 4.72 = p´ x 4.6 + (1-p´) x 4.78 ➔ p´= 0.33

The result indicates that the error probability must change from 35% to 33% for the decision maker to become indifferent between selecting either of the two solutions: fixed or dynamic solution.

The "certainty equivalent" value of the dynamic solution option is obtained by considering the expected utility of the dynamic selection:

U(EC)=UE(dynamic selection)

Ln(EC) = 4.71➔ $EC = e^{4,71} = 111.05$ €/ha

The "certainty equivalent" value provides us information on the decision maker behavior, which is indifferent between getting a "certainty equivalent" consumption value of 111.05 €/ha and risking obtaining an increase in suppression costs and a reduction in the natural resources value saved, equal to a consumption value of 112.19 €/ha.

Finally, the "risk premium" understood as the maximum amount a decision maker would be willing to pay to not encounter risk is given the difference between the expected value of the fixed solution and the determined "certainty equivalent" value. For the case presented here the risk premium is:

PR=VE(fixed solution) - EC =112.19 -111.05 = 1.14 €/ha

That is, the maximum amount the decision maker is willing to give up to avoid risk is 1.14 €/ha. In other words, is the maximum amount that a risk averse decision maker is willing to accept (pay) to avoid facing risk. Incorporating this information in the utilities versus consumption graphic we can show both "the certainty equivalent' value and the "risk premium" (Figure 2).

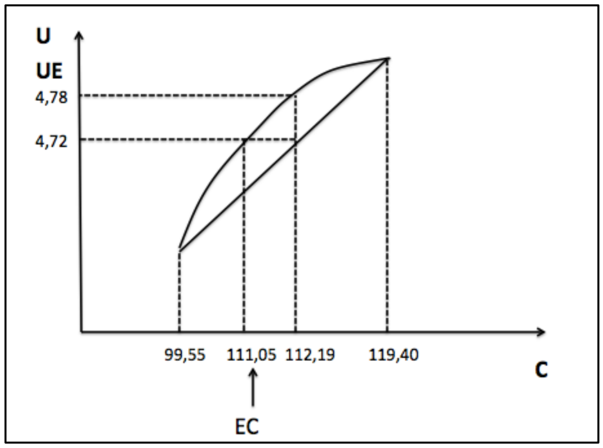

Figure 2. Graphic of the expected utilities versus expected consumption values obtained from the contingent plans analysis.

Discussion

The operational management of forest fires suppression activates is complex given that the fire suppression technical management takes place under conditions of uncertainty. The gathering of agents/actors experience in prior process of capitalization (collection of incident manager's experiences) is not frequent. This implies a continued loss of prior experiences by not establishing protocols to properly collect, filter, order and classify the information. The lack of customarily monitoring fire suppression related data is one the most limiting factors in reducing the lack of knowledge about forest fires suppression actions.

The capitalization of fire suppression experiences and scientific studies provide important opportunities for operational improvements and to progressively increase fire suppression operations. In this regard decision making processes based on reducing the level of uncertainty lead to more efficient solutions in fire suppression plans. The methodology proposed here is a first step in the use of economic and prediction analysis tools helping to clarify the horizon of uncertainty scenarios.

Using the expected utility to analyze the uncertainty and risk provides diagnosing opportunities for selection of fire suppression strategies within the framework of fire suppression and forest landscape management. Understanding decision makers risk posture under uncertainty scenarios and how it may affect their decision making process provides new insights into fire suppression operational plans that include a strategic combination of firefighting resources, suppression costs and the affected resources net-value change.

Including in the analysis factors related to the probability of success provides in a comparative way the "benefits" in terms of the resulting payments from the analysis of the defined contingent plans. One of the most important parts of this methodology contributing to the analytical process is the utility function selection. There are different options for studying the quality of the information each information provides varying from mathematical to econometric functions providing results in terms of productivity (Cobb-Douglas, CES, Translog, etc.).

In this work we have chosen the utility function derived from the Napier logarithm for the consumption variable. This function characterize the decision maker risk posture behavior given the concavity of the utility curve (Graphic 2). It is important to point out that in conditions of uncertainty in the operational management of emergencies decision makers tend to adopt a risk aversion posture in the possible application of more efficient contingent plans, but without experience about their results or the success probabilities are difficult to ascertain, thus to establish.

In any case, the experiences from commercial decision making under conditions of uncertainty (investments on equipment and goods, stocks investments, purchasing of financial goods, and insurance purchases, etc.), and also scientific research on uncertainty and risk microeconomic models provide a solid foundation for development of planning and decision support tools for forest fire suppression operations.

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