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Spatio-temporal effects of human drivers on fire danger in Mediterranean Chile

Efectos espacio-temporales de los factores humanos en el peligro de incendio en Chile mediterráneo

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SUMMARY

The aim of this study was to analyze how human factors, specifically land use and cover change (LUCC), influence wildfire danger in a mediterranean region of central Chile. Main drivers of LUCC were associated with changes in socio-economic conditions, which had strong effects on the structure of the landscape and on the danger of wildfires. Ignition and flammability were evaluated as key components of fire danger. Ignition probability was modeled for 1999 and 2009 using an autologistic regression, based on fire records from Corporación Nacional Forestal (CONAF) and geographic, biophysical, and socioeconomic databases. Flammability was assessed by combining the National Vegetation Cadastre of 1999 and its update of 2009, and the fuel model developed by Julio (1995). Spatiotemporal analysis of flammability was performed and related with primary LUCC processes, namely, plantation expansion, forest regrowth, and agricultural abandonment. We combined the ignition probability and flammability analysis to produce wildfire danger maps. Results show that fire danger is a dynamic indicator that depends largely on human factors. By 1999, the area under high fire danger comprised 31,399 ha, whereas by 2009 this area had increased by 54,705 ha. For both periods, wildfire danger had a similar spatial distribution, concentrating near main roads, cities, and larger towns (26.3 % of the high fire danger area). Also high fire danger areas concentrated over zones covered by exotic forest plantations (33.2 %). These results provide a basis for a more effective design of fire control strategies.

Key words: fire danger, probabilities of ignition, flammability, landscape.

RESUMEN

El objetivo de este estudio fue analizar la influencia de factores humanos, en específico del cambio de cobertura y uso de suelo (CCUS), en el peligro de incendios forestales en una región mediterránea de Chile. Para ello, se evaluó la probabilidad de ignición y la inflamabilidad del paisaje como componentes clave del peligro de incendio. La probabilidad de ignición fue determinada a través de una de regresión autologística para los años 1999 y 2009, utilizando como base los registros de la Corporación Nacional Forestal y variables generadas a partir de bases de datos geográficas. La inflamabilidad se evaluó mediante la combinación de las categorías de vegetación presentes en el Catastro y evaluación de recursos vegetacionales de Chile de 1999 y su actualización de 2009, y el modelo de combustible desarrollado por Julio (1995). Se llevó a cabo un análisis espacio-temporal de inflamabilidad el que se relacionó con los principales procesos CCUS (expansión de plantaciones, regeneración forestal y abandono de tierras agrícolas). Se combinó la probabilidad de ignición y el análisis de inflamabilidad para producir mapas de peligro de incendios. Los resultados mostraron que el peligro de incendio es un indicador dinámico que depende en gran medida de factores humanos. En 1999, las áreas de alto peligro concentraron 31.399 hectáreas, mientras que para el año 2009 esta área aumentó en 54.705 ha. En ambos períodos el peligro tuvo una distribución espacial similar, concentrándose cerca de las carreteras, principales ciudades (26,3 % de la zona de peligro) y en áreas cubiertas por plantaciones forestales (33,2 % de la superficie bajo peligro alto de incendio).

Palabras clave: peligro de incendio, probabilidad de ignición, inflamabilidad, paisaje.

INTRODUCTION

Wildfire is one of the most important factors driving environmental transformations in a wide variety of ecosystems (FAO 2007). While physical processes involved in combustion are theoretically simple, understanding the relative influence of human factors in determining wildfire is an ongoing task (Guettouche *et al*. 2011). Human influence on wildfire has been classified into three categories: institutional, human-environment interaction, and human values placed on land use (Cardille *et al*. 2001). Institutional and social policies facilitate or constrain certain management alternatives that model landscape. Such drivers have mostly a temporal dimension, longer than the appearance of change, reason why often an historical perspective is needed. Moreover, human-environment interaction involves the evolution of the landscape (e.g. land tenure, land use patterns, and infrastructure) along with changes in population behavior and preferences that can increase the probability of ignition (Chuvieco 2010). Also, there is clear evidence that the role of humans on shifting land use and cover, and therefore on landscape structure and function, has increased wildfire danger, particularly in Mediterranean regions (Moreira *et al*. 2001). These changes have been associated with particular processes of abandonment of agricultural lands and post afforestation resulting in a higher fuel load that is generated in the process (Viedma *et al*. 2006).

The present study analyses how human factors, particularly land use and cover change, influence wildfire danger taking as a case study the Maule Region in south-central Chile. We follow the framework proposed by Chuvieco *et al*. (2010), which considers fire danger as the potential that a fire ignites or propagates. We focus on two main components of fire danger which are ignition and flammability. Due to the nature of the region and principal causes of fire, we focus on understanding the human causes of ignition. In turn, flammability as a component of the fire spread potential was related to fuel load and continuity.

METHODS

In past decades, the Maule Region (35° 25′ 36″ S, 71° 39′ 78″ O) has undergone a widespread and fast land use and cover change mainly driven by socio-economic conditions, which in turn, have had strong effects on the structure of the landscape and on wildfire danger. Two key components of fire danger were evaluated, namely human-set ignition probabilities and flammability. We determined ignition probabilities for years 1999 and 2009 using autologistic regressions estimated based on fire records from Corporación Nacional Forestal (CONAF), and geographic, biophysical and socioeconomic databases. Integrated wildfire danger maps were constructed by the combination of higher probabilities estimated from ignition maps (probabilities over 0.7) and higher flammability determined from the fuel load maps for each period (over 3,000 kg m^{-2}).

Also, landscape flammability maps were constructed combining the land cover classes from the National Vegetation Cadastre (1999) (henceforth Catastro) and its update (2009) developed by CONAF and the fuel model generated by Julio (1995). The matching between land covers used by Julio (1995) and those from Catastro is presented in appendix 1. In addition we conducted a spatio-temporal (1999-2009) analysis of main land use and cover change using the Land Change Modeler extension (Argis 9.3). Since the focus of the study was the assessment of the influence of land use and cover change processes on wildfire danger, changes in land cover were regrouped accordingly as follows: a) plantation expansion included changes of use on any land class (excluding forest exotic plantation) to forest exotic plantation, differentiating between those caused by afforestation (plantation on agricultural land and shrublands) and those caused by substitution (plantations established on arboreous shrublands and native forest areas); b) forest regrowth included changes from shrublands of any nature to secondary native forests; c) agricultural abandonment included changes from agricultural land to any category excluding forest exotic plantations. Using map algebra we assessed areas of change in fuel properties and related these areas to particular land use and cover change processes.

RESULTS

Land use and cover change and fire danger. Between 1999 and 2009, 27.4 % of the Maule Region's area (2,188 km^2) registered land use and cover change, while the rest of the landscape persisted with the same coverage. In 1999 the landscape was dominated by agricultural land (27.8 %), followed by shrubs (20.5 %), forest plantations almost exclusively of *Pinus radiata* D. Don (18.4 %), secondary native forests (14 %) and arboreous shrublands (9.2 %).

Adult plantation expansion occurred at annual rates of 2.55 % and 1.23 % for the processes of afforestation and substitution, respectively, increasing the total area of plantations from 493,959 ha in 1999 to 588,580 ha in 2009 (197,322 ha from afforestation and 39,617 ha from substitution). Plantation expansion increased fuel load and fuel availability, having different impacts on other parameters of flammability, as the rate of linear spread and resistance to control. Increases in fuel load ranged between 3 and 40 Mg ha^{-1} (figure 1). The largest increase on fuel load was associated to the change from agricultural land to exotic plantations.

Forest regrowth occurred at an annual rate of 1.08 %. On one hand, this process increased fuel load where initial coverage was dense and semidense shrubland, with presence of dominant species like *Nothofagus obliqua* Mirb., *Acacia caven* Mol. and *Chusquea spp.*, but decreased fuel load in areas where the land use and cover change transition led to a final cover of open forest of *Nothofagus antarctica* (G. Forster) and *Nothofagus pumilio* (Poepp *et* Endl.). Increases in fuel load and fuel availability were associated with a decrease on propagation speed and resistant to the first control line.

The loss of agricultural land occurred at an annual rate of 0.51 %, and affected 49,337 ha. This implied an increase in fuel load that ranged between 6 Mg ha^{-1} to 45 Mg ha^{-1}, which led to an increase of available fuel varying from 1,902 kg m^{-2} to 3,533 kg m^{-2}. This process was also associated with a decrease in the speed of propagation and resistant to control. The largest increase in fuel load was associated with the change from annual pastures to secondary forest, while the lowest increase was observed as a result of the change from agricultural land to open shrubland (figure 2).

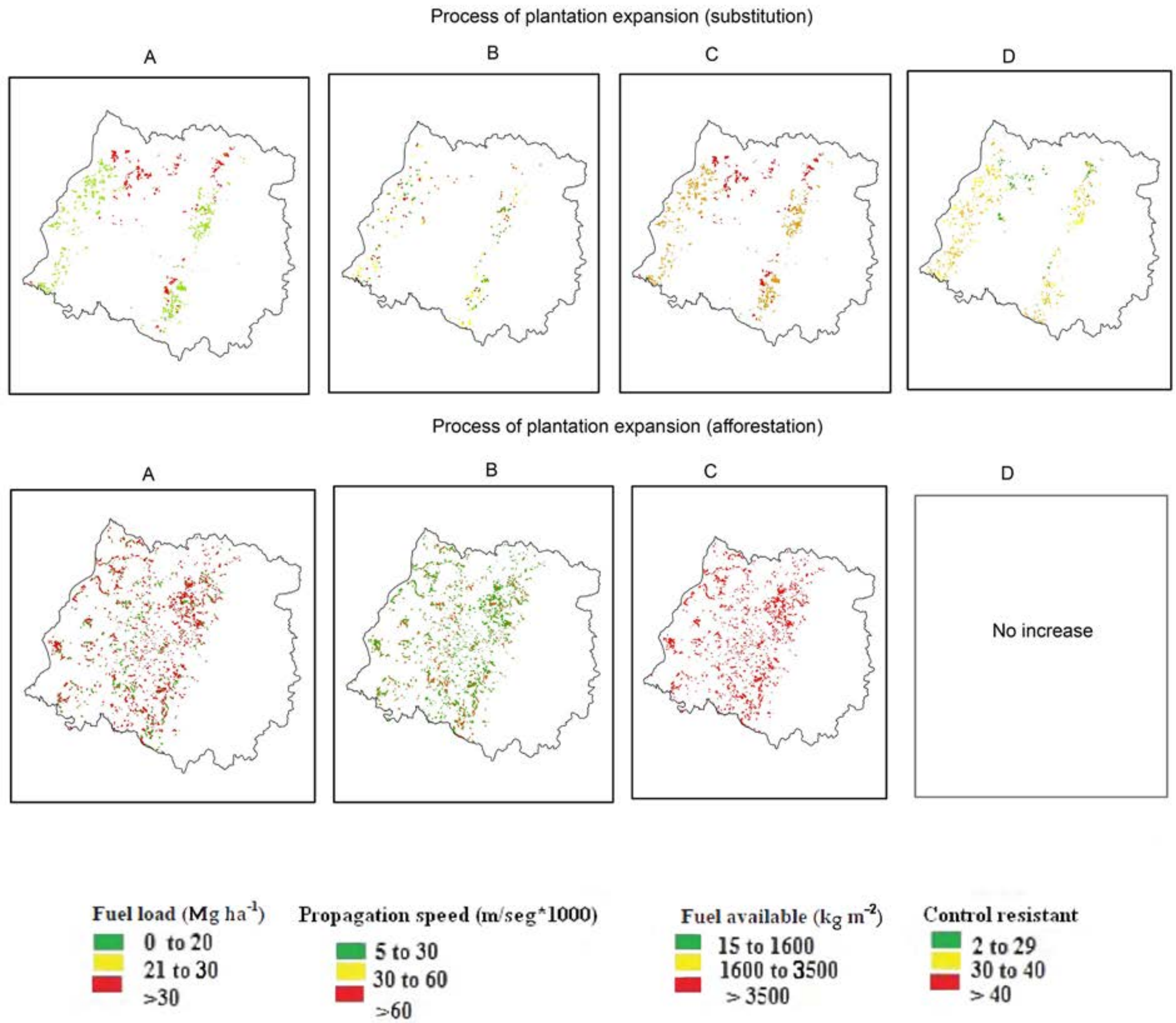

Figure 1. Spatial distribution of increase in fuel parameters, resulting from plantation expansion by substitution and afforestation.
Distribución espacial del incremento en los parámetros de combustible, resultante de la expansión de plantaciones por sustitución y reforestación.

Ignition probabilities. Autologistic regressions for both years presented[1] an overall accuracy above 70 %. For both periods, explanatory variables were distance to towns and cities, and also distance to streams and water bodies. This means that probabilities of ignition increased as distances from these covers decreased (table 1).

Fuel load was a significant explanatory variable for the period 2009 indicating an increase in ignition probabilities in areas with higher fuel load, corroborating that landscape changes during this period have increased fuel load and flammability.

Fire danger. Wildfire danger assessment analyzed two key components of wildfire: the likelihood of an area to ignite and the potential of fire propagation and duration, which relate to the properties of the fuel. Results show that fire danger is a dynamic indicator that depends in great measure of human factors. By 1999 danger area comprised 12,056 ha whereas in 2009 this area had increased by 42,649 ha. For both periods fire danger had a similar spatial distribution, concentrating near principal roads, cities and larger towns (26.3 % of the area), and also on areas covered by exotic forest plantations (33.2 %) and agricultural land (18 %). In the second year a large danger area was located in the central valley of the Maule Region in zones covered by shrublands (59.7 %) (figure 3).

DISCUSSION

According to historical statistics from CONAF, in the Maule Region 99 % of fire ignitions are associated with

[1] Jorge Silva *et al.*, unpublished data.

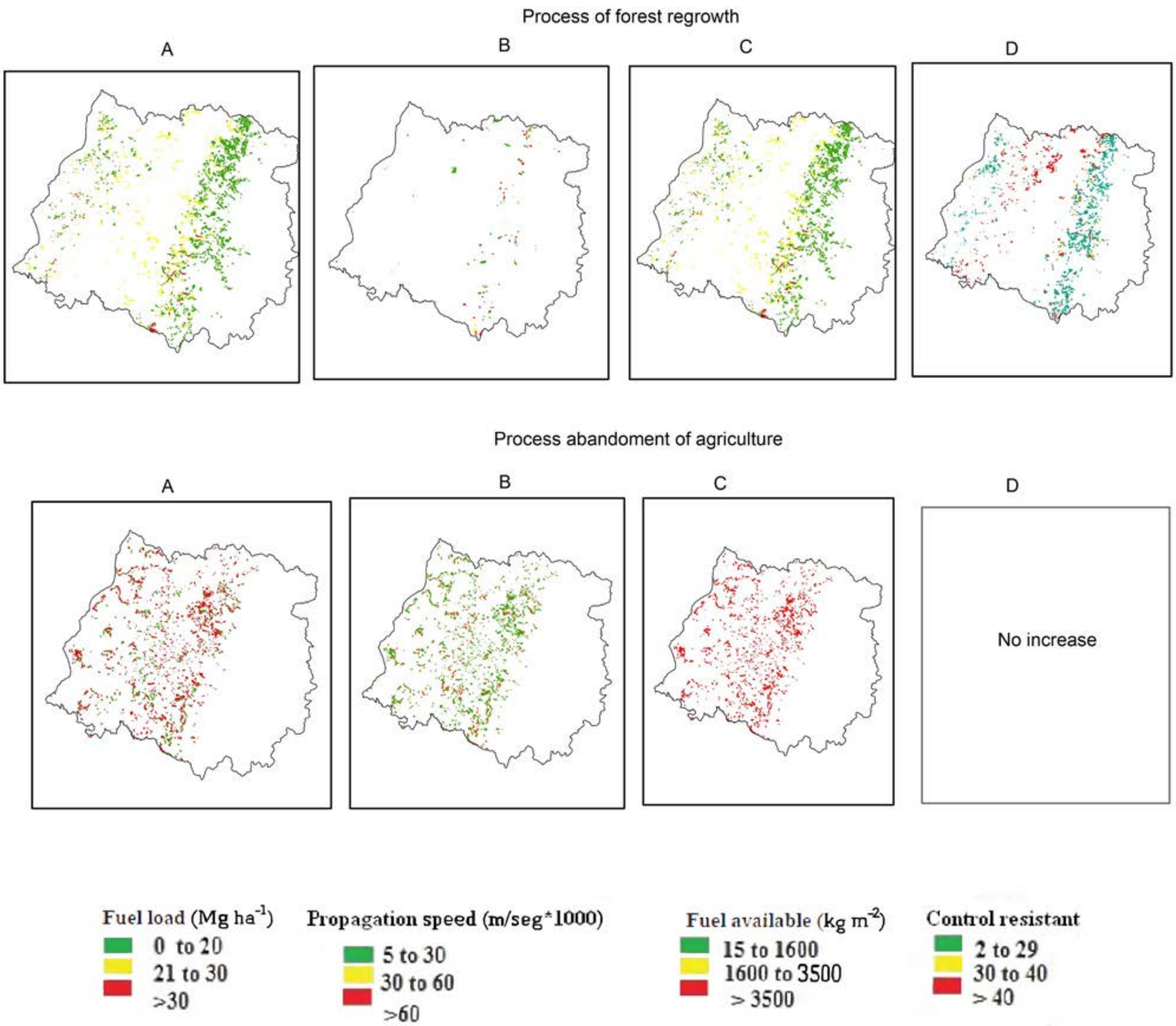

Figure 2. Spatial distribution of increase in fuel parameters, resulting from for forest regrowth and agricultural abandonment processes.
Distribución especial del incremento de los parámetros de incendio, resultante del recrecimiento forestal y el abandono agrícola.

human causes. In this sense, the results generated in this study are consistent with these records, showing flammability and ignition probabilities were determined by variables related to human activity. Other studies have showed a positive relationship between population density and number of wildfires in different Mediterranean zones (Cardille *et al*. 2001). Also a positive relationship has been found between increase in urban population and wildfire (Cardille *et al*. 2001). Demographic statistics of Maule Region show an increase in population between both periods of analyses for almost the whole Region, however the highest rates of increase correspond to the municipalities of Talca and Maule, where an increase in fire danger was found.

The most relevant land use and cover change in the period 1999-2009, namely plantation expansion and agricultural abandonment, have contributed to increase the wildfire danger area, as indicated by ignition probabilities and fuel load. Plantations began to expand in the early 1970´s and grew rapidly, mainly on the Coastal Range, but recently they have also reached the central zone of the region and the Andes range. A recent study reveals that plantations in the coastal area of the Maule Region increased nearly ten-fold between 1975 and 2007 at an average annual rate of 6.4 %, with important implications for the landscape (Nahuelhual *et al*. 2012).

In the case of agricultural abandonment, while forest industrial development has created dynamic labor mar-

Table 1. Results from the autologistic regressions for years 1999 and 2009.
Resultados de las regresiones autologísticas para los años 1999 y 2009.

Variable	Year			
	1999		2009	
	Coefficient	*P* value	Coefficient	*P* value
Constant	-19.603	< 0.001	-16.616	< 0.001
Distance to towns (km)	-0.057	0.002	-0.133	< 0.001
Distance to rivers and streams (km)	-0.073	< 0.001	-0.114	< 0.001
Distance to water bodies (km)	-0.003	0.563	-0.002	0.716
Distance to protected areas (km)	0.003	0.492	-0.001	0.801
Average temperature of warmest month of the previous season (degree Celcious)	0.059	0.35	-0.025	0.695
Total precipitation of the previous season (mm)	-0.104	0.477	-0.055	0.827
Southern exposure (binary variable equal to 1 if pixel shows southern exposure and 0 otherwise)	-0.339	0.025	0.201	0.31
Fuel load (Mg ha^{-1})	0.015	0.664	0.092	0.03
yW	36.985	< 0.001	35.497	< 0.001
Total precision	0.702		0.708	
Sensibility	0.667		0.698	
Specificity	0.737		0.719	

Source: Jorge Silva *et al*., unpublished data.

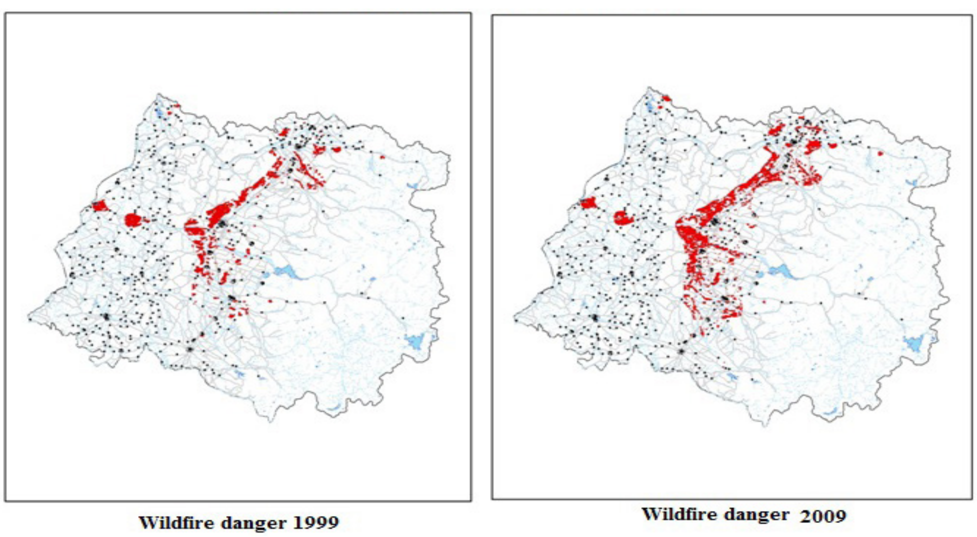

Figure 3. Wildfire danger maps for years 1999 and 2009.
Mapas de peligro de incendios para los años 1999 y 2009.

kets, it has also endangered both traditional agricultural patterns and local development strategies (Moreira *et al.* 2001), driving abandonment of agricultural lands.

Wildfire danger is a dynamic phenomenon that changes its spatial representation by both climate variability and human factors. Among the many human factors that affect wildfire danger is land use and cover change. The combination of this type of analysis with fuel properties and probability of ignition provides valuable information for prevention and fire management (Cardille *et al*. 2001), especially when both can serve as predictive models.

CONCLUSIONS

This study has been able to identify key human factors that affect wildfire danger in a Mediterranean Region of

Chile. The processes of plantation expansion and agricultural abandonment together with the expansion of human activity near cities and on the urban-rural interface are key factors in increasing wildfire danger.

While this work focuses on past trends, future research should improve the analysis by creating future scenarios of land use and social development so they can be used in a predictive way.

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Appendix 1

Combustibility modeling by Julio *et al.* (1995) shows five groups that comprise 31 combustibility models, including a sixth group comprised by three different situations associated to non-combustible areas. Groups' descriptions and their respective models are showed in the Appendix. These groups were linked to Catastro land use categories.

Group	General description	Symbol	Specific description	Catastro land use categories
I	Meadows, pastures, and agricultural crops	PCH		
		PCH1	Hygromorphic dense	----
		PCH2	Hygromorphic sparse	----
		PCH3	Mesomorphic dense	----
		PCH4	Mesomorphic sparse	Perennial grasslands Annual grasslands
		PCH5	Vineyards and orchards	Agricultural land Rotation crop, pasture
II	Shrublands and secondary forest	MT		
		MT01	Dense mesomorphic shurblands and secondary forest	Dense esclerofic secondary forest and shrubland and open and semidense Ciprés de la cordillera forest
		MT02	Medium density and sparse density mesomorphic shurblands and secondary forest	Open and semidense esclerofic secondary forest and shrubland and open and semidense cipres de la cordillera forest
		MT03	Dense hygromorphic shurblands and secondary forest	Dense secondary forest of Roble-Raulí-Coihue, Lenga, and Roble-Hualo forests
		MT04	Medium density and sparse density hygromorphic shurblands and secondary forest	Open, and semidense secondary forest of Roble-Raulí-Coihue, formation, Lenga formation, and Roble-Hualo
		MT05	Formations with predominance of *Chusquea sp*	
		MT06	Formations with predominance of *Ulex sp*	
		MT07	Secondary forest with formations different from evergreen forest	Open, semi-dense and dense secondary forest of Roble-Raulí-Coihue, Lenga, and Roble-Hualo
		MT08	Secondary forest that correspond to evergreen forest.	Open evergreen secondary forest
III	Native tree formations	BN		
		BN01	Alerzales	
		BN02	Araucarias	
		BN03	Dense *Nothofagus* formations	Dense native forest of Roble-Raulí-Coihue, Lenga, and Roble-Hualo
		BN04	*Nothofagus and evergreen* medium density formations	Semi-dense native forest of Roble-Raulí-Coihue, Lenga and Roble-Hualo
		BN05	*Nothofagus and evergreen* sparse density formations	Open native forest of Roble-Raulí-Coihue, Lenga, and Roble-Hualo
IV	Plantation	PL		
		PL01	New plantations of conifers without management from 0 to 3 years	Young plantation or recently harvest
		PL02	Young plantations of conifers without management from 4 to 11 years	
		PL03	Adult plantations of conifers without management from 12 a 17 years	

		PL04	Mayor plantations of conifers without management 17 years	
		PL05	Young plantations of conifers with management 4 a 11 years	
		PL06	Adults plantations of conifers with management 12 to 17 years	*Pinus radiata* plantation
		PL07	Larger plantations of conifers with management over 17 years	
		PL08	New *Eucalyptus* plantations from 0 to 3 years	
		PL09	Young *Eucalyptus* plantations from 4 to 10 years	*Eucalyptus spp.* plantation
		PL10	Larger *Eucalyptus* plantations over 10 years	
		PL11	Broadleaf and mixed plantations	
V	Waste from clearcutting forestry exploitation	DX		
		DX01	Waste from clearcutting of conifers and eucalyptus	
		DX02	Waste from forest exploitation (trapping) of thickets and native forest	
VI	Land without vegetation	SV		
		SV01	Body water	River, lakes, reservoirs, beaches
		SV02	Urban areas	Town and cities
		SV03	Bare soil	Fallow soil

Document available at: http://ftp.forestaluchile.cl/LINFOR/articulos/Modelaci%C3%B3n%20de%20Combustibles.pdf and CONAF *et al.* (1999).