Estimation of Live Fuel Moisture Content From MODIS Images for Fire Danger Assessment in Southern Gran Chaco

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***Abstract*—Moisture content of live fuels (LFMC) is one of the main factors determining fuel flammability and, therefore, a key indicator of fire danger. In this study, we modeled the relationship between spectral indices derived from satellite imagery and field estimations of LFMC in the Chaco Serrano subregion; then, we analyzed the relationship between fire danger estimations based on LFMC calculations and fire activity. Empirical LFMC models fitted for grasslands, Chaco Serrano forests, and glossy privet forests may be considered very accurate $R^2 > 0.80$, whereas the model corresponding to shrublands still needs to be improved ($R^2 = 0.57$). Monthly maps of fire danger reflected the occurrence of fires consistently during years of both high and low fire activity. Most fires occurred mainly in areas with high or extreme fire danger, demonstrating a clear relationship between LFMC and fire activity in the Chaco Serrano subregion. Our LFMC models may be useful to assess the spatiotemporal distribution of fire danger in the Chaco Serrano subregion using remote sensing data. The associated fire danger maps represent a valuable tool for improving decision making processes to organize early warning and fire suppression activities.**

***Index Terms*—Fires, modeling, moisture measurement, prediction methods, risk analysis.**

I. Introduction

MOISTURE content of vegetation is one of the main factors determining fuel flammability and, therefore, a key indicator of fire danger [1]. Fuel flammability tends to decrease as fuel moisture content increases, due to a delay in fire ignition and a lower rate of spread [2]–[4]. Additionally, fuel moisture content data have proven to be useful to predict the number of fire events and burned area [5]. Thence, many studies addressing fire behavior and fire danger have focused on the prediction of the moisture content of fuels [1], [6]. In fact, some authors proposed a classification of fire danger based upon the moisture content of live fuels (LFMC), assigning a high fire danger to values between 60% and 80% and an extreme fire danger to those below 60% [6].

The most accurate method to determine LFMC is to make field surveys and collect fuel samples [7]. Samples are weighted to determine the fresh weight and then they are oven-dried to determine dry weight. The fuel moisture content is calculated as a percentage of dry weight [8], [9]. Nevertheless, field estimations of LFMC are costly and time consuming; therefore, their extrapolation over space and time is difficult [7], [10]. For this reason, fitting models to estimate LFMC using variables that are more easily measured and applicable for spatial generalization is considered a valuable tool for environmental managers [9], [11]–[14]. In addition, these LFMC estimations can be used to feed quasi-real-time fire operative systems [15].

Given that variations in vegetation moisture content affect the spectral signature of vegetation [16], LFMC can be estimated using remote sensing data [7]. For this purpose, one of the most widely accepted approaches is to fit empirical models using field estimations of LFMC and spectral indices [10], [14], [17], [18]. The main advantages of this approach are that these models are easy to fit and provide accurate estimates [7], [17], [18]. However, these empirical relationships may vary with the type of sensor used and sites sampled, meaning that empirical models are likely to be valid only at the local scale and for the specific sensor used for their calibration [7], [19].

Recent studies have estimated LFMC by inverting models of simulated reflectance (radiative transfer models, RTM) [7], [19]–[22]. These models attempt to establish more general associations through the physical relationship between LFMC and the reflectance measured by satellite imagery. Given that these relationships are independent of sensors and site conditions, RTMs should be more general than the empirical models. Nevertheless, the process of selection and parameterization is more complex and time-consuming for RTMs than for empirical models. Moreover, it requires more auxiliary information [7], because inversion is not singular, i.e.: certain reflectance values can result from different combinations of the input variables that feed the inversion [23]. Additionally, some studies have reported similar accuracy levels between RTMs and empirical models [7], suggesting that this higher complexity does not necessarily translate into improved model accuracy.

The Chaco ecoregion is the most extensive seasonally dry forest in Latin America [24], [25], with fires being one of the

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main disturbances in the area [26], [27]. Fires contribute to forest loss and degradation, reducing biodiversity [28]–[30] and affecting ecosystem services, such as soil protection and water retention [31], [32]; thus, forests become hotspots for conservation. The Chaco Serrano subregion is one of the areas most affected by fires. Maps of burned areas derived from Landsat imagery (30-m spatial resolution) indicated that nearly 300 000 ha burned between 1999 and 2013 [33], [34]. The region also shows high fire frequency and great number of large fires [33]. Additionally, this area is home to more than 850 000 people, and almost one-half of the total number of buildings are located in the wildland-urban interface (WUI) [34], where the proximity between fuels and buildings increases the risk of damages to people and private property [36]. In the last decades, human intervention in fire regimes has produced extensive fires with several negative impacts at the landscape level, including the reduction and degradation of native forests [37], [38], soil erosion [31], pollution of important freshwater reservoirs [32], household destruction, and livestock death.

In this study, we modeled the relationship between spectral indices and field estimations of LFMC; then, we analyzed the relationship between LFMC and fire activity. To the best of our knowledge, the only study that attempted to estimate vegetation moisture in Chaco region using remote sensing data and RTMs [39] suggested that the latter models are not well suited for the heterogeneous canopies of the Dry Chaco. The specific goals of our research were: 1) to monitor LFMC dynamics in the dominant vegetation communities of the Chaco Serrano throughout the fire season; 2) to build empirical models relating field estimations of LFMC and vegetation reflectance; and 3) to analyze the relationship between fire danger estimations based on LFMC calculations and fire activity. Our research is the first attempt to monitor moisture content of live fuels in the Chaco Serrano subregion using remote sensing data and within the framework of fire danger.

II. Materials and Methods

A. Study Area

We conducted the study in the Sierras Chicas (810 000 ha), located in Córdoba province and corresponding to the southern portion of the seasonally dry forest of Gran Chaco in Argentina (see Fig. 1). This mountain range stretches north–south for about 245 km, with an altitudinal range between 500 and 1947 m a.s.l. The climate is temperate semiarid with a monsoonal rain regime, with a mean annual rainfall of 850 mm and a mean annual temperature of 17.3 °C (National Meteorological Service of Argentina, data from the 1999–2014 period). Rainfall is concentrated between October and March (spring and summer). Winter is dry and mild, with relatively high temperatures in August and September, when most fires occur [33]. Between 1999 and 2013, more than 300 000 ha burned, with a high fire frequency being recorded in many areas (see Fig. 1).

The Chaco Serrano vegetation consists of a mosaic of forests, shrublands, and grasslands. These vegetation physiognomies are represented along the elevation gradient, although in variable proportions. Chaco Serrano forests, dominated by *Lithraea molleoides* are more frequent below 900 m; shrublands dominated by *Acacia caven* and *L. molleoides* are more frequent below 1300 m; and grasslands dominated by *Festuca hieronymi* are usually found above 900 m [40]. Native vegetation is under different pressures: grazing, invasion by exotic plants (mainly the Chinese tree *Ligustrum lucidum* commonly known as glossy privet), selective logging and fires. In addition, rural inhabitants use fire to promote forage regrowth during the dry season [28], [41], [42].

More than 850,000 people live in the area, and almost half of the buildings ($\approx$144 000) are located in WUI areas, where fire risk is high [34]. Moreover, the National Institute of Statistics and Censuses of Argentina (INDEC) estimates an overall population growth for this area close to 33% from 2010 to 2025. This will increase the WUI area and, consequently, the number of people and buildings at risk [34].

B. Field Estimations of Live Fuel Moisture Content

We monitored LFMC during 2012 and 2013 fire seasons (June–December). We established five 50×50 m^2 plots in each of the four main vegetation types of Sierras Chicas (20 plots in total, Fig. 1): Chaco Serrano forests, shrublands, grasslands, and exotic glossy privet forests [40], [41]. In each sampling area, the distance between plots was larger than 1000 m to avoid spatial autocorrelation issues [43].

Each plot was sampled approximately every three weeks, and each sampling consisted of collecting the terminal twigs ($\varnothing < 0.5$ cm) and leaves of woody fuels, and the leaves and stems of grasses and herbs [8]. Material was collected from several individuals. Plots were divided in half, and during each visit two subsamples of live fuels (one per half plot) were taken to ensure the representativeness of samples. Subsamples were collected and transported in sealed bags; the sum of the fresh weight of both subsamples ranged between 100 and 200 g. The subsamples were weighed in the laboratory to determine fresh weight (W_f) and oven-dried at 105 °C until constant weight ($\approx$72 hs) to determine dry weight (W_d) [8], [44]. LFMC (%) was determined as: $100^*(W_f - W_d)/W_d$ [9]; LFMC values of the two subsamples were averaged to obtain the LFMC value for each plot and date. Samples were collected between 11 A.M. and 5 P.M., which is the time of the day at which most fires occur [8], [12].

Precipitations differed among sampling years (see Fig. 2). Early precipitations occurred in 2012, resulting in positive rainfall anomalies in August, September, and October (30.6, 64.6 and 118.8 mm versus averages of 6.7, 33.0, and 86.0 mm, respectively). Contrarily, in 2013, rainfall anomalies were negative from July to October (see Fig. 2).

C. LFMC Modeling

The independent variables included various spectral indices derived from the Moderate Resolution Imaging Spectroradiometer (MODIS). We used the land surface reflectance product MYD09A1 (500 m of spatial resolution; freely available at: http://daac.ornl.gov/MODIS/modis.shtml), which provides a composite image every eight days. For each sampling year,

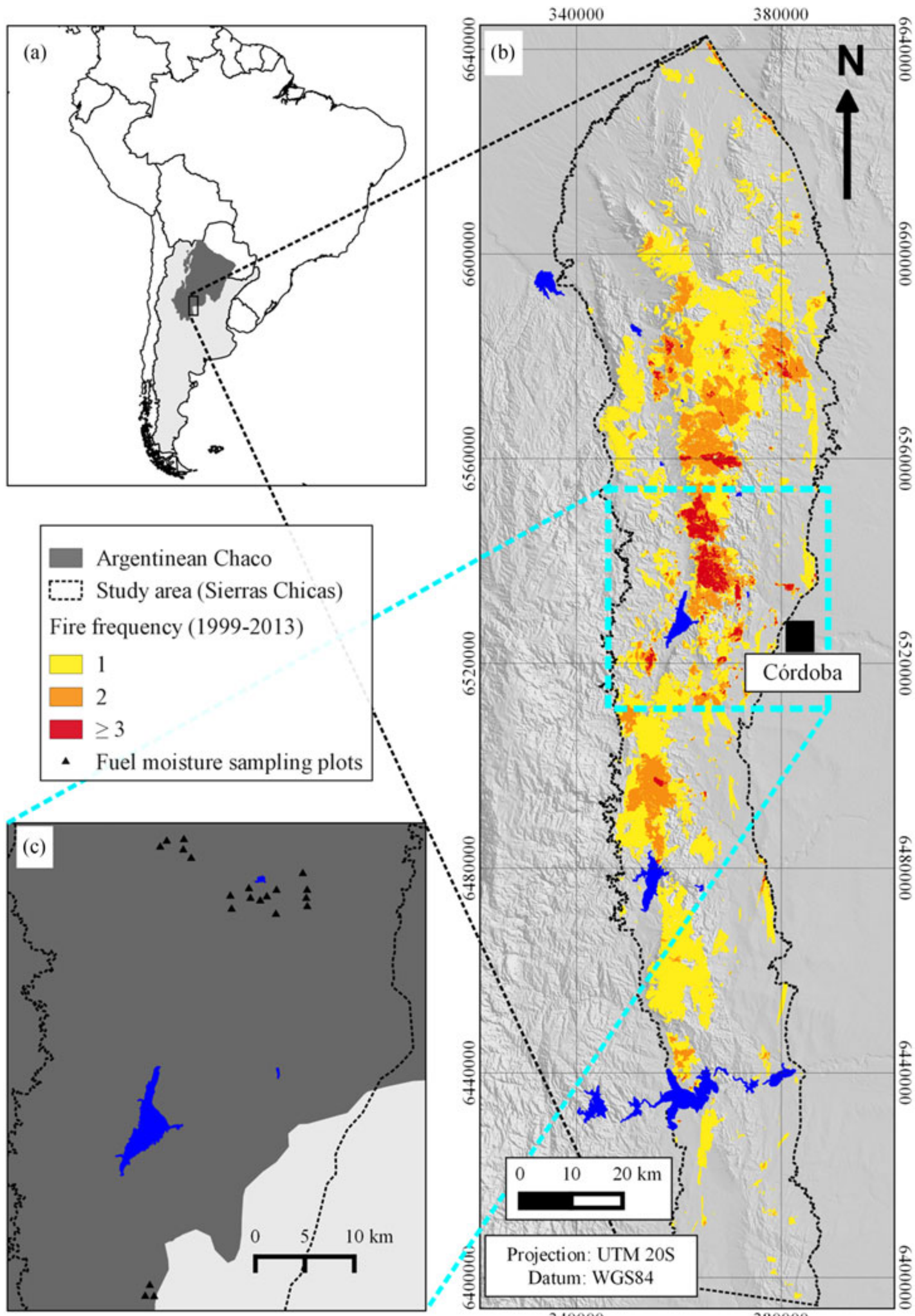

Fig. 1. Fire frequency (1999–2013) in Sierras Chicas of Córdoba province, Argentina, and distribution of sampling plots.

we used a 31-image stack corresponding to the May–December period (days of year 121 to 361). Using these stacks, we calculated various spectral indices that are known to highlight different characteristics of vegetation: NDVI, SAVI, EVI, GEMI, VARI, $NDII_6$, NDWI, GVMI, Integral, Derivative Green-Red, Derivative Red-NIR, Derivative NIR-SWIR, MSI, SR, and VIgreen [7], [10], [14], [45]. Indices based on the visible and NIR bands are estimators of vegetation chlorophyll content, whereas indices derived from the SWIR bands are estimators of vegetation water content [10], [14], [46].

Once we obtained the stack for each spectral index, we built the corresponding time series for the pixels associated with each of the sampling plots. Then, we applied the Savitsky-Golay filter to smooth the typical noise of these time series [47], [48]. This smoothing technique is widely used because it preserves features of the initial distribution, such as relative maxima and minima and peak width [48]. The smoothed value for a certain date was calculated using a temporal window of ± 3 MYD09A1 dates (24 days). Then, we associated the field estimation of LFMC with the smoothed time series of the different spectral indices corresponding to the closest date of the MODIS product, before or after the sampling date.

The relationship between the field-estimated LFMC for each land cover type and the independent variables was

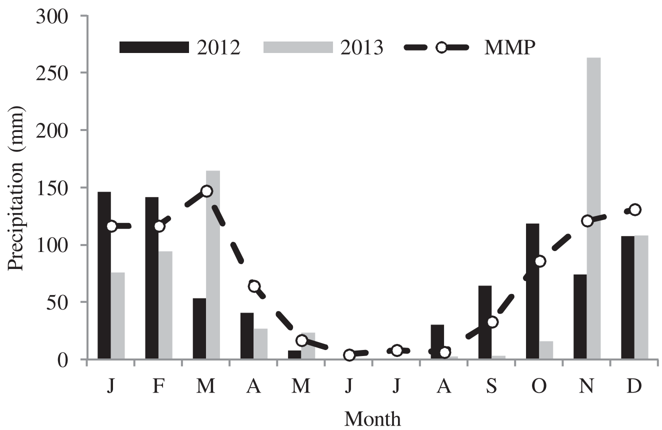

Fig. 2. Mean monthly precipitation (MMP, 1999–2014) and accumulated monthly precipitation during 2012 and 2013 in Sierras Chicas of Córdoba, Argentina (Source: National Meteorological Service of Argentina, Córdoba airport weather station).

analyzed using mixed linear models. We considered the temporal correlation of field LFMC estimations as repeated measures [49]. Previously, we discarded independent variables that had Spearman coefficients of correlation $|r| \geq 0.90$ [50]. Then, we fitted the models using stepwise backward elimination and the final models only included significant predictor variables $(P < 0.05)$ [49].

D. LFMC and Fire Activity

LFMC models were used to estimate LFMC maps for our study area during the fire seasons of 2003, 2012, and 2013. The first and last years were characterized by a high fire activity and large burned areas (2003: 55 000 ha burned and 2013: 40 000 ha burned) [33], [34], whereas the burned area in 2012 was small (<10 000 ha according to the Fire Management Plan of Córdoba Province). Then, we assessed fire danger for these fire seasons based on the classification proposed by Weise *et al.* [6].

We used a land cover map to select the appropriate LFMC model for each pixel. The map was derived from SPOT 5 images acquired on September 7 2012, and a Landsat 8 OLI scene (Path/Row: 229/81) acquired on August 6 2013. The Landsat 8 image was used in the northern portion of Sierras Chicas, due to the presence of clouds in SPOT 5 images. This map was obtained by performing supervised classifications using support vector machines. The Radial Basis Function kernel was used, and the C and γ parameters required for this kernel were determined using a tenfold cross validation performed via the package "e1071" [51] in R [52]. The ranges considered for these parameters were $C \in [2^{-5}, 2^{15}]$ and $\gamma \in [2^{-15}, 2^{3}]$, according to previous recommendations [53]. The overall accuracy of both maps was $\approx 93\%$ (see more details in [34]). The land cover map (10-m spatial resolution) was resampled to match the spatial resolution of the MODIS reflectance products (500 m) using the majority filter. Then, fire danger maps were derived considering low fire danger if LFMC $> 120\%$, moderate if LFMC was between 80% and 120%, high between 60% and 80% and extreme if LFMC $< 60\%$ [6].

To assess the performance of the fire danger maps, we analyzed the proportion of burned pixels of each vegetation type that corresponded to each fire danger class. To accomplish this, we determined LFMC before the 2003, 2006, 2009, and 2013 fires (88 900 ha burned). Additionally, we compared the LFMC values before fires with the values of the same date but one year earlier (no-fire-years: 2002, 2005, 2008, and 2012, respectively).

III. Results

A. Seasonal Variability of Live Fuel Moisture

The dynamics of LFMC differed among land cover types both in range of LFMC values and their variations throughout the fire season. The difference in rainfall distribution among study years affected LFMC dynamics, although differently in each land cover type.

All land cover types showed an increasing tendency in LFMC after August 2012 precipitations. Then, values seemed to have stabilized between November and December, except for grasslands (see Fig. 3). On the contrary, during 2013 fire season, LFMC in grasslands, shrublands, and Chaco Serrano forests exhibited a relatively constant or slightly decreasing tendency until the beginning of the seasonal precipitations (see Figs. 2 and 3). In glossy privet forests, LFMC decreased in varied proportions in all plots during 2013 until the beginning of precipitations. The decline in LFMC from July to October/November 2013 reached up to 16% for Chaco Serrano forests (see Fig. 3: 92.0–75.6 = 16.4%), 26% for grasslands, and 68% for glossy privet forests, whereas shrublands did not show any remarkable change (see Fig. 3).

The average LFMC values for 2013 fire season for grasslands, shrublands, and Chaco Serrano forests were $\approx$15% lower than in 2012, whereas for glossy privet forests this difference was considerably higher, reaching values almost 60% lower than in 2012 (see Fig. 4). The negative rainfall anomalies observed from July to October 2013 affected all individuals in glossy privet forests, causing the loss of most of their foliage by October (J. P. Argañaraz, unpublished data).

B. Predictive Models of LFMC

LFMC models fitted for grasslands, Chaco Serrano forests, and glossy privet forests explained more than 80% of the total variability (see Table I). Contrarily, the model fitted for shrublands showed a lower accuracy, explaining 57% of the total variability. Of the eight spectral indices included in model fitting, only four were retained as significant predictors (see Table I), with EVI being selected as a predictor in three models, GVMI and Integral in two models, and NDVI in only one model.

The equations to estimate LFMC for the dominant land cover types of the Chaco Serrano subregion using spectral indices are as follows:

$$\mathrm{LFMC}_{\mathrm{Grasslands}} = 540.09\ \mathrm{EVI} - 31.16 \tag{1}$$

$$\mathrm{LFMC}_{\mathrm{ChacoSerrano}} = 1.88\ \mathrm{Integral} + 246.39\ \mathrm{NDVI} - 63.06 \tag{2}$$

$$\mathrm{LFMC}_{\mathrm{Shrublands}} = 334.53\ \mathrm{EVI} - 305.98\ \mathrm{GVMI} - 7.05\ \mathrm{Integral} + 199.72 \tag{3}$$

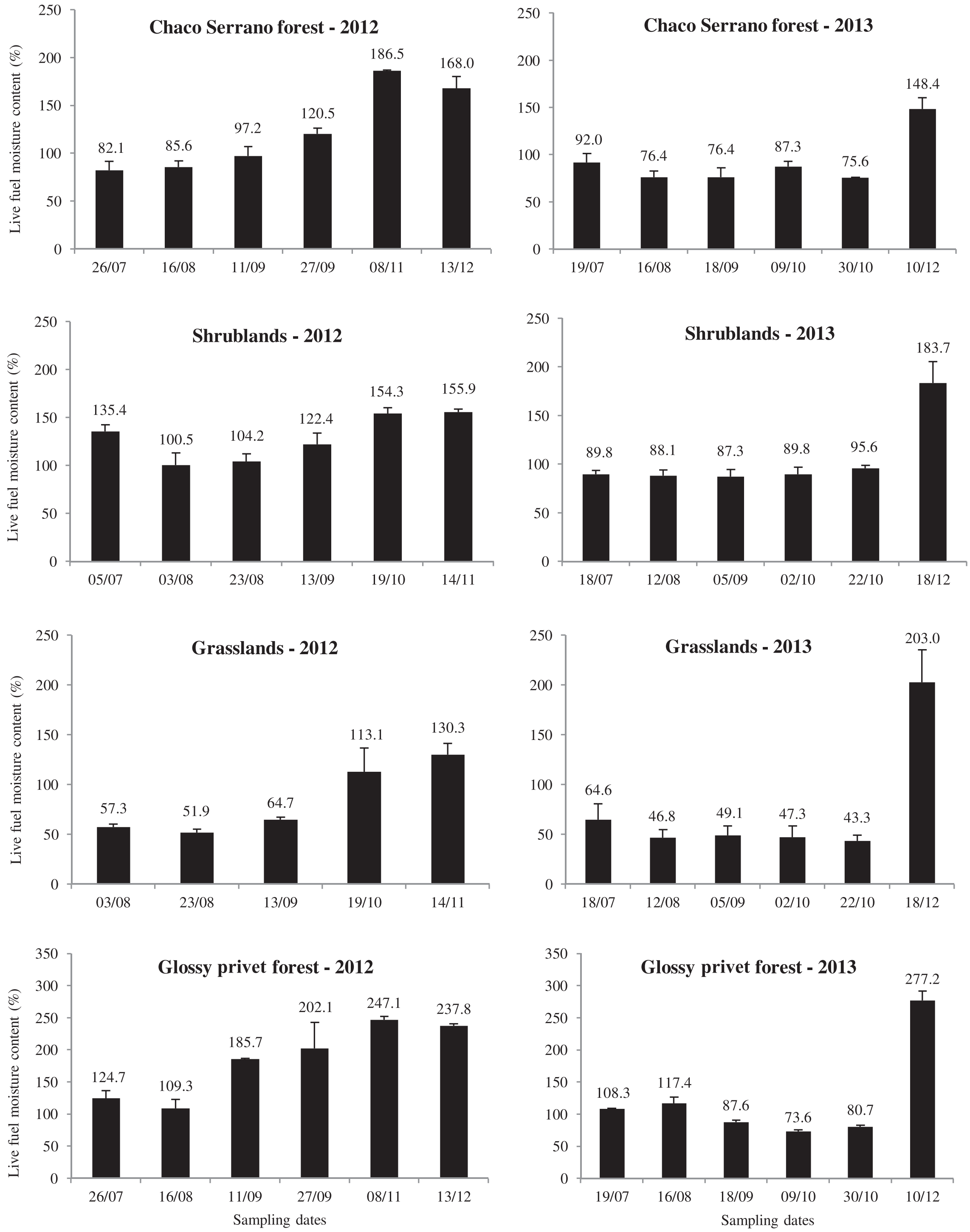

Fig. 3. Fuel moisture dynamics throughout 2012 and 2013 fire seasons for the four dominant vegetation types in Sierras Chicas, Córdoba, Argentina.

$$\mathrm{LFMC}_{\mathrm{GlossyPrivet}} = 456.99\ \mathrm{EVI} + 165.29\ \mathrm{GVMI} - 20.23 \quad (4)$$

C. Relationship Between LFMC and Fire Activity

Fire danger in Sierras Chicas differed between years with high fire activity (2003 and 2013) and low fire activity (2012) (see Fig. 5). For instance, in 2003, the area with high and extreme fire danger increased from June to September/October. At the beginning of November, fire danger was still moderate to high in 60% of our study area, with the burned area reaching more than 18 000 ha. In December, fire danger was still moderate to high in 45% of Sierras Chicas, with the burned area covering 800 ha (see Fig. 5). In that year, the first important rainfall event occurred on October 30 (50 mm) and the second one, on

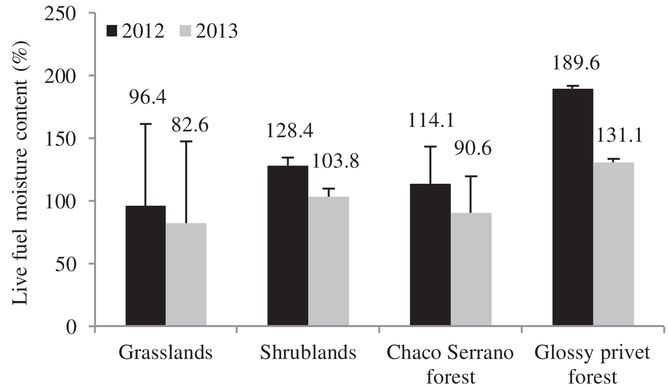

Fig. 4. Average values of live fuel moisture content during the 2012 and 2013 fire seasons in the four dominant vegetation types in Sierras Chicas, Córdoba, Argentina.

TABLE I
COEFFICIENTS AND SIGNIFICANCE OF THE SPECTRAL INDICES INCLUDED IN THE EMPIRICAL MODELS OF LIVE FUEL MOISTURE CONTENT FITTED FOR THE DOMINANT VEGETATION TYPES OF SIERRAS CHICAS, CÓRDOBA, ARGENTINA

Spectral indices[1]	Grasslands ($R^2 = 0.88$; $N = 54$)		Chaco Serrano forest ($R^2 = 0.86$; $N = 52$)		Shrublands ($R^2 = 0.57$; $N = 26$)		Glossy privet ($R^2 = 0.81$; $N = 55$)	
	Coef.	p-value	Coef.	p-value	Coef.	p-value	Coef.	p-value
NDVI	–	–	140.92	< 0.0001	–	–	–	–
EVI	540.09	< 0.0001	111.34	< 0.05	334.53	< 0.01	456.99	< 0.0001
GVMI	–	NS	–	–	–305.98	< 0.05	165.29	< 0.05
Integral	–	NS	–	–	-7.05	< 0.01	–	NS
NDII6	–	–	–	NS	–	–	–	–
NDWI	–	NS	–	–	–	–	–	–
SR	–	–	–	–	–	–	–	NS
VARI	–	NS		–	–		–	–

Spectral indices subset included at the moment of model fitting, after discarding those having high Spearman correlation $|r| > 0.90$. The level of significance is only reported for those indices included in each case. NS: Non-significant ($p > 0.05$).

November 29 (60 mm). On the other hand, during 2013 fire season, danger increased, reaching almost 45% of Sierras Chicas, with high to extreme fire danger in September and October (almost 40 000 ha burned in September). Then, fire danger decreased considerably in November (263 mm rainfall), and was mostly low in December (108 mm rainfall).

The low fire activity observed in 2012 is in agreement with the LFMC dynamics. Fire danger increased from June to September, although a reduction in the area with extreme fire danger was observed between August and September (18–12% of Sierras Chicas; Fig. 5), coinciding with the increasing tendency of fuel moisture content observed during field sampling. At the beginning of October, fire danger was considerably lower than in the previous month of the same year and than in the same month of 2003 and 2013 (see Fig. 5). In November, the area with moderate to extreme fire danger decreased considerably (29% of Sierras Chicas) and by the beginning of December, fire danger was moderate only in 17% of Sierras Chicas.

Overall, fires burned mainly in areas with high and extreme fire danger (LFMC $< 80\%$), accounting for 60% of the burned pixels (see Table II). The areas with moderate fire danger accounted for 37% of the burned pixels. In the case of grasslands and Chaco Serrano forests, 97% of the burned areas exhibited high or extreme fire danger. Instead, fire danger was mostly moderate in burned shrublands and high or extreme only in 16% (see Table II). The histograms of the LFMC before fires indicated lower moisture values in years of fire occurrence than in the previous years, when no fires occurred. This difference was greater in grasslands and Chaco Serrano forests than in shrublands (see Fig. 6).

IV. DISCUSSION

LFMC dynamics in the Chaco Serrano subregion was influenced by the distribution of precipitations. The increasing values of field LFMC estimations following the early precipitations of 2012 (see Fig. 2) indicate the ability of both native and exotic vegetation to respond rapidly, even in the recess growth period (April–October). On the other hand, the reduction or maintenance of low LFMC in Chaco Serrano forests and shrublands throughout the 2013 fire season is in agreement with the environmental conditions described for the fire season in the Western Chaco region [54], [55], and could be related to the loss of foliage due to the severe negative rainfall anomaly of 2013.

The high LFMC values recorded in grasslands and glossy privet forests during the field surveys of December 2013 were related to the presence of a high proportion of primary tissues with high water content (foliage), typical of a new period of vegetative growth [6], [8], [56]. The lower moisture content observed in grasslands in both years of this study, together with the accumulation of standing dead fuels throughout the fire season and the architecture of grasses, explain the greater flammability and fire frequency reported for these types of fuels than for those of shrublands and forests [33], [57]. This implies a greater fire danger if the degradation of native forests continues as well as their replacement by shrublands and grasslands, as it has been observed in our study area [28].

The native woody vegetation seems to be more resistant to drought than the exotic glossy privet, which lost most of its foliage under the driest conditions of 2013. This phenomenon occurs because the native woody species prioritize a safer water transport strategy whereas the exotic species prioritize the capacity of conduction, which makes them more vulnerable to cavitation [58]. Despite this, LFMC in glossy privet forests was considerably higher than in the native vegetation of Chaco Serrano, probably due to its evergreen foliage and its tendency to invade more humid areas [41]. This might explain the lower fire activity observed in these exotic forests (J. P. Argañaraz, unpublished data). Additionally, this species showed characteristics of low flammability and it has been proposed as a potential firebreak [59]. Nevertheless, during years of drought they can lose most of the foliage, generating a thick bed of dead fuels on the ground and therefore increasing fire danger in peri-urban areas, where the greatest invasion occurs [41].

The goodness of fit of our models suggests that the MODIS reflectance products and derived indices have great potential to

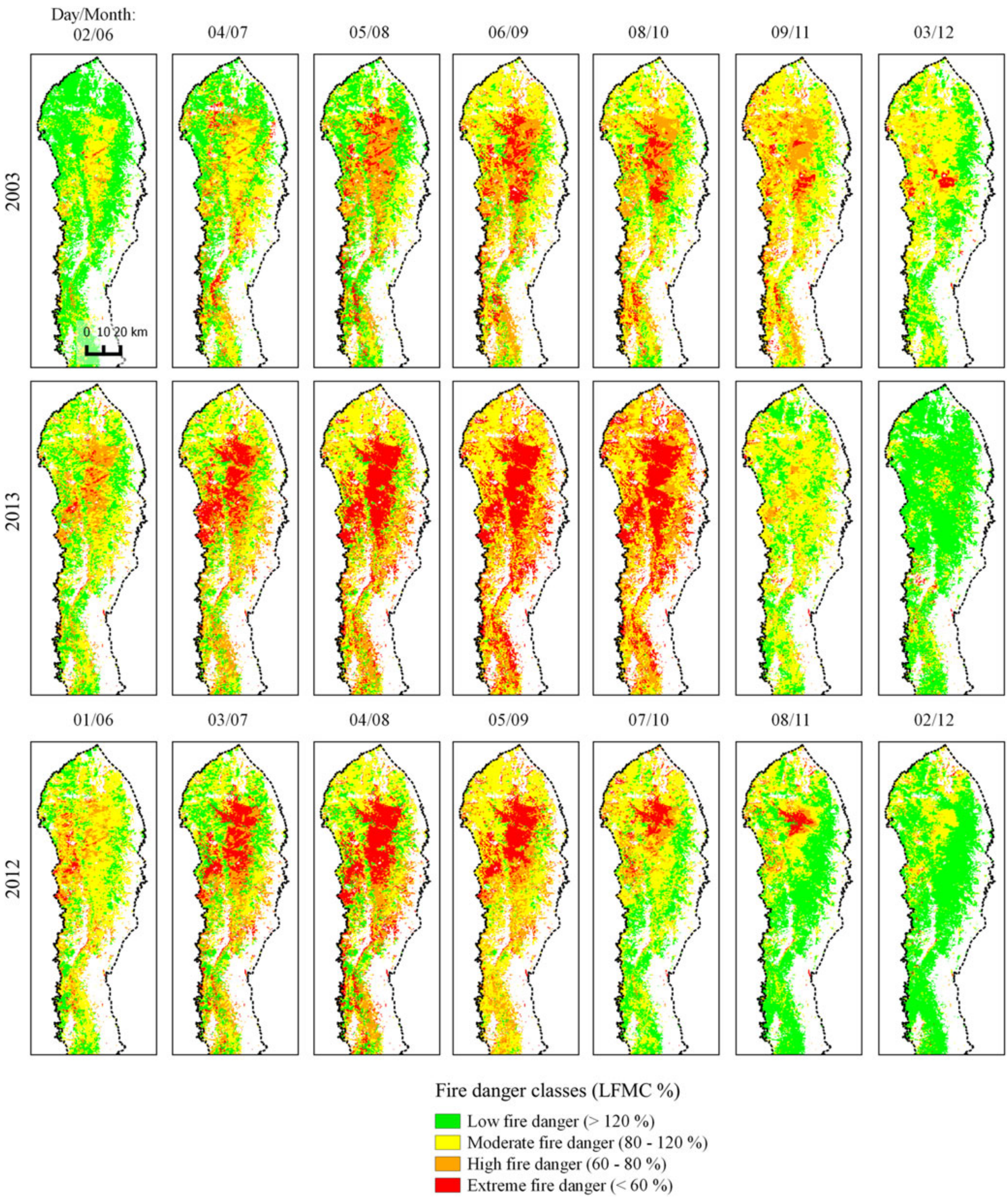

Fig. 5. Monthly fire danger during fire seasons of high fire activity (2003 and 2013) and low fire activity (2012). The fire danger classes are based on [6].

predict LFMC in the Chaco Serrano subregion. These results indicate that our LFMC models might be a useful tool to monitor the spatiotemporal distribution of the flammability of fuels. The lower goodness of fit observed for shrublands is probably related to a smaller sample size (see Table I). Some of our sampling plots burned in 2013, and there were extreme fire danger conditions that delayed some field surveys. Furthermore, another source of error might be the fact that shrublands in our study area tend to

TABLE II
NUMBER OF BURNED PIXELS (AND PERCENTAGE) OF DIFFERENT FIRE DANGER CLASSES FOR EACH VEGETATION TYPE IN THE SIERRAS CHICAS OF CÓRDOBA, ARGENTINA

Fire danger	Chaco Serrano forest	Grasslands	Shrublands	Total
Low	0 (0.0)	0 (0.0)	137 (7.7)	137 (3.5)
Moderate	31 (3.6)	31 (2.5)	1362 (76.6)	1424 (36.7)
High/Extreme	838 (96.4)	1197 (97.5)	280 (15.7)	2315 (59.7)
Total	869	1228	1779	3876

Pixel size: ≈500 m. Burned area (88 900 ha, based on landsat derived burned polygons) includes fires occurring in 2003, 2006, 2009, and 2013.

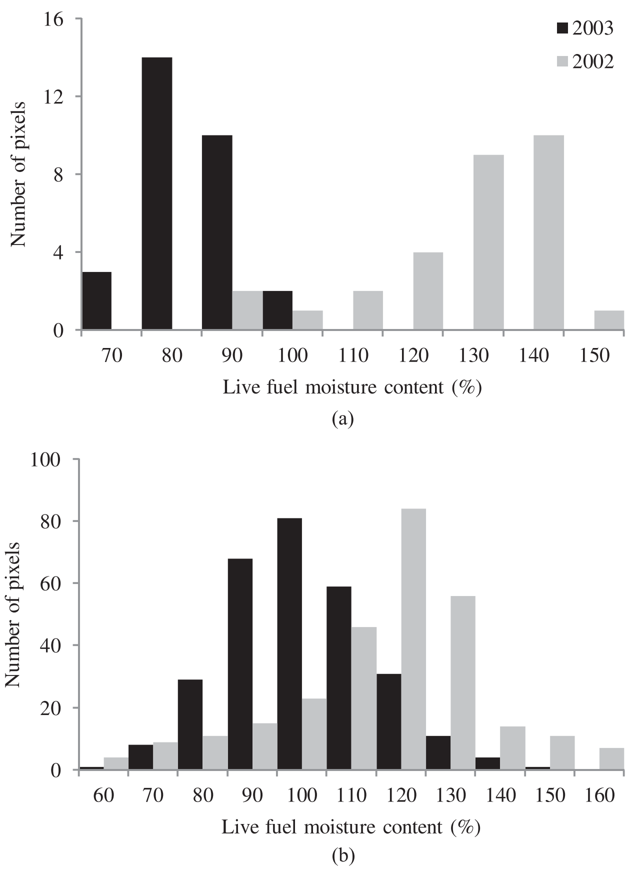

Fig. 6. Live fuel moisture content values before fires in pixels of (a) Chaco Serrano forests and (b) shrublands burned on November of 2003 as compared to the same date in 2002.

be open and hold a high proportion of grasses [40], which determines that the reflectance of each pixel is not dependent only on woody species. Accordingly, we recommend continuing with field surveys to improve the LFMC models for shrublands. The goodness of fit of our models for grasslands, native forests, and exotic glossy privet forests are similar to those reported in the literature for different ecosystems worldwide, both from empirical models [10], [18], [45], [60]–[62] and theoretical models of simulated reflectance (RTM) [7], [19], [21].

Of the set of spectral indices predicting LFMC in our study area, two are estimators of chlorophyll content of vegetation (NDVI and EVI), and the other two are estimators of water content (GVMI and Integral) [10], [14], [46], [63]. LFMC models for the woody land covers (shrubland, Chaco Serrano forest, and glossy privet forest) included both types of spectral indices (green and water indices), as in most of the models fitted for woody species worldwide [7], [45], [60], [62]. Instead, the only significant predictor of LFMC in grasslands was the green index EVI. This relationship between green indices and LFMC is especially common in grasslands due to the link between plant chlorophyll content and plant water content [17], [20], [56], [64]–[66]. Moreover, even though the NIR and SWIR bands are the most sensitive to changes in water content of vegetation [16], the visible region of the electromagnetic spectrum also shows certain sensitivity to these changes [64], [66]. This would explain the identification of green indices as significant predictors of LFMC in all the studied land cover types of our Chaco Serrano landscape.

The maps of fire danger derived from our LFMC models consistently reflected the occurrence of fires during years of high (2003 and 2013) and low (2012) fire activity. Additionally, fires burned mainly in areas with high or extreme fire danger, and LFMC values detected before fires were lower than on the same date of the previous no-fire-year, demonstrating a clear relationship between LFMC and fire activity in the Chaco Serrano subregion. Particularly, the low LFMC observed in September and October 2013 seems to justify the higher fire activity in that year than in 2012. These months also coincide with spring warming, a condition that promotes fuel desiccation and more severe fires [55]. This suggests that our models would be a valuable tool for an early warning system and, therefore, for more effective decision making in fire risk management. In this context, it is also important to consider that LFMC and derived fire danger maps do not completely explain fire occurrence, since low LFMC values are a necessary condition for, but not a cause of, fires [5].

One way of improving the assessment of fire danger is by integrating LFMC estimations with other variables of fire danger [67], [68]. Even though fuel flammability decreases as LFMC increases [3], [4], [69], at the species level, flammability also depends on other features, such as dead branch retention, plant architecture, and chemical composition of tissues [57], [70], [71]. Fire danger evaluations must also consider variables related to ignition sources and conditions that favor fire spread, such as fuel accumulation rates and thresholds of fuel biomass needed for a fire to spread [54]. Even with low LFMC, the absence of ignitions will translate into zero fires, meaning that low LFMC values do not necessarily predict higher fire activity, although they provide the appropriate conditions. A preventive forestry management plan depends on handling multiple complex factors, both in the social and physical environments [72].

Moreover, in the context of decision making, it is important to consider the uncertainty of estimations and how it might affect the accuracy of fire danger estimations [2], [73]. Estimation errors can compromise both the safety of the personnel involved in prescribed fires or fire suppression activities during uncontrolled fires and the resources used for these purposes [6]. The accuracy values of our LFMC models also provide information about the uncertainty of fuel moisture estimates for Sierras Chicas. Accordingly, it will be necessary to improve the accuracy of LFMC estimations of shrublands (which occupy 35% of our study area), before this model can be used for decision making. Additionally, considering that LFMC estimations for each pixel depend on the land cover type, their accuracy will also depend on the availability of an accurate and updated land cover map.

In conclusion, our LFMC estimations provide useful information for fire danger assessment and therefore for fire management in the Chaco Serrano subregion. The fire danger maps obtained here represent a supporting tool for decision making that might be useful in an early warning system and in the planning of prevention activities over space and time. Moreover, they could help to organize fire suppression activities and plan prescribed fires [2], [7]. The latter, aimed at avoiding the excessive accumulation of fuels, are gaining acceptance as a tool for integrated fire management worldwide [7], [74], [75].

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