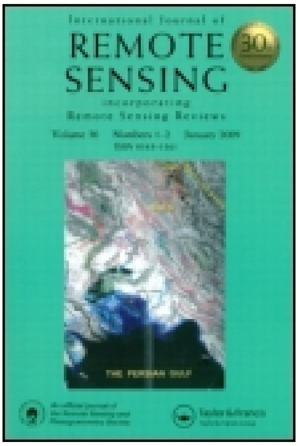

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Fire patterns in north-eastern Argentina: influences of climate and land use/cover

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Fires are one of the most frequent disturbances on terrestrial ecosystems, thus making their understanding and prediction crucial for their management. While the fuels condition are linked to well-known environmental factors, the ignition triggering agents are less understood and may display a more stochastic behaviour. We studied the regional relationship between the fire density and frequency, climate and land use/cover in the north-east region of Argentina using Moderate Resolution Imaging Spectroradiometer (MODIS) hotspots data, daily weather reports and land use/cover data at national level. The pre-fire water availability index showed a significantly negative relationship with hotspot densities ($r^2 = 0.51$, $p < 0.01$). The uncultivated land coverage, mainly represented by natural grasslands, was positively associated with the fire density (for Entre Rios, $r^2 = 0.74$, $p < 0.0001$ and for Corrientes, $r^2 = 0.67$, $p < 0.0001$). The results highlight the potential of remote sensing for fire monitoring in this region and its value in urgently needed policies for fire control and management.

1. Introduction

Fires represent one of the most important factors affecting natural vegetation worldwide. During the year 2000, satellite information revealed that more than 350 million ha were burned worldwide (FAO 2006). From an ecological standpoint, fires affect directly the natural succession of ecosystems and indirectly water and energy balances, biogeochemical cycles and local climate, among other variables (e.g. Crutzen and Andreae 1990, Hoffmann *et al.* 2003). From a land-management perspective, fires can be an essential tool in both protected lands and rangelands, favouring vegetation regrowth, enhancing forage quality and speeding up nutrient cycling (Menaut *et al.* 1993; Pivello and Coutinho 1996), among others.

In Argentina, during the period 2004–2006, available fire databases indicated an average of around 750 000 ha burned every year, affecting a wide range of vegetation types, including grasslands (53%), shrublands (27%) and natural forests (18%) (PNMF 2003–2006). According to regional authorities, fires can be caused by negligence or accidents (26%), intentionally for rangeland management (13%) and they can

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be originated by natural causes (4%); however, a significant percentage of fires present unknown causes (57%) (PNMF 2003–2006). Available statistics highlight three main aspects of fires in Argentina: their areal importance, a very high intra- and inter-annual variability and the scarce knowledge about the causal agents (fires with unknown causes).

The north-eastern region of Argentina is one of the areas most affected by fires. In this region, fires present two density peaks during the spring and autumn. Fire density begins to augment in June–July (winter in the Southern Hemisphere) when the senescence of vegetation tissues increase as a result of the first winter frosts and the onset of several environmental conditions, such as winds with a NNE direction, 20% of humidity (especially at noon) and 60 km h^{-1} of speed, among others. The end of this fire season is variable according to the beginning of the rainy season (October–November). On the other hand, the autumn fires are concentrated in the period between March and May, when the quantity and quality of fuel materials accumulated during the summer season could favour their combustion. The monthly distribution of natural fires should be associated with the lightning's distribution, because they are considered the main causal factors of natural fires. Lightnings are events related to the presence of electric storms, and in this region, they occur mainly from September to January. However, man-made fires used for agricultural management are common from August to May. In late winter or early spring, farmers use fires to the reduce woody cover and to maintain the balance between herbaceous and woody plants (Cornacchione *et al.* 2001) or to remove dead and dry biomass accumulated during the previous growing season that could inhibit new plant growth. In the autumn, arson fires are commonly used to promote vegetation regrowth suitable for livestock before the winter season. Local experts suggest the end of the autumn as the best period for prescribed burning. In this time, the summer species (C_4 grasses) are in a dormant stage, and biomass burning could favour the germination and growth of winter species (C_3 grasses and legumes), which improve forage quality and production timing. In addition, local experts suggest autumn fires rather than summer fires due to the weather conditions prevailing at this time of year being less risky for the occurrence and spread of fires. However, despite summer fires not usually being recommended, their frequency is high because of the fuel, climatic and human conditions of this season (Kunst *et al.* 2003).

Despite the enormous efforts made by Government Institutions to provide information about fire occurrence and distribution, some flaws make this information less reliable for the application to fire management to more detailed spatial and temporal scales. The subjectivity associated with the number and diversity of informants of fire features (i.e. forest service, civil defence, fire fighters and police) and the presence of some areas with a low density of informants are the main disadvantages of the precision of these reports. In this context, remote sensing can provide a valuable and objective tool for the detection, understanding and control of fire events. From the spectral information corresponding to the visible and infrared bands of the electromagnetic spectrum, it is possible to: (1) detect sites with anomalous temperature (so called hotspots) using diverse algorithms (e.g. Dozier 1981, Matson and Dozier 1981, Giglio *et al.* 1999, 2003, Briess *et al.* 2003); (2) quantify burned areas at different spatial and temporal scales (e.g. Chuvieco and Martin 1994, Riaño *et al.* 2007, Chuvieco *et al.* 2008); (3) explore the relationship between fire occurrence and control factors (e.g. Hoffman *et al.* 2003, Di Bella *et al.* 2006) and (4) generate a fire-risk index using the vegetation water conditions from remotely sensed data (e.g. Hunt and Rock 1989, Cohen 1991, Chuvieco *et al.* 1999, 2002).

Taking into account the importance of fires in north-eastern Argentina, the main objective of this article was to characterize the spatial and temporal distribution of fires during three years (2004–2007) and to explore the relationships between some fire events variables (annual, monthly and seasonal frequency) and climate (precipitation, potential evapotranspiration), main vegetation types or land use/cover variables.

2. Materials and methods

The study area involves 429 000 km^2 of fire-prone land (Amaya *et al.* 2003). The area is divided in five provinces: Corrientes, Misiones, Chaco, Santa Fe and Entre Rios (figure 1). The region hosts a precipitation gradient ranging from 1700 mm yr^{-1} in the NE to 800 mm yr^{-1} in the SW and a mean annual temperature between 16–22°C. Three

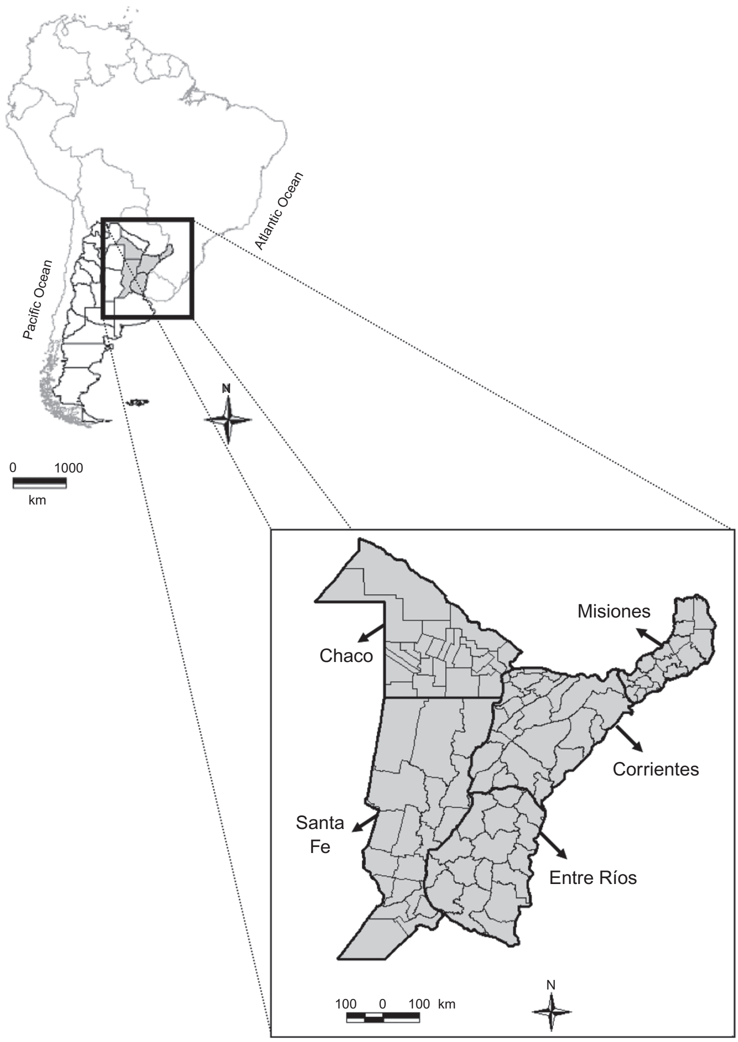

Figure 1. Study area, including the provinces of Chaco, Santa Fe, Misiones, Corrientes and Entre Rios (north-eastern Argentina).

climate types are distinguished in the area: subtropical with dry season, subtropical without dry season and humid temperate. Around 64% of this surface is covered by grasslands and 19% by tree plantations. Mainly, soils do not present limitations for agricultural crops, and cultivated pastures are the dominant vegetation. The province of Misiones was originally covered by rainforest, and it has been mostly replaced by annual crops and tree plantations. Areas subject to frequent water logging/flooding or salinity are still under the native vegetation of grasslands and savannahs in most of their territory. These areas are dominated by extensive livestock handling activities, where the stocking rate ranges between 188 and 201 kg ha^{-1} and it is determined mainly by primary productivity and forage quality (Oesterheld *et al.* 1998).

The study region is severely affected by fire every year. Between 2004 and 2006, this area concentrated around 7378 fires, affecting approximately 175 000 ha (PNMF 2003–2006). The fire density peak is usually concentrated in the spring and summer seasons. The province of Corrientes has the highest incidence of fires. Although the causes that originate 80% of fires are unknown in official reports, it is well known that fires are used as a common land-management practice, since it is considered a cost-effective way to increase forage quality and quantity, and to clear the land for agricultural activities.

In order to analyse the spatial and temporal patterns of fires, we used hotspots databases. The locations of hotspots were daily obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board Terra and Aqua platforms for the period January 2004–July 2007. The capture, preprocess and detection of hotspots were performed by the Argentine Space Agency (CONAE, *Comisión Nacional de Actividades Espaciales*) taking into account certain algorithms previously developed – MODIS Hotspots version 4, MOD14 (Giglio *et al.* 2003). The MODIS data set was processed to extract latitude, longitude, date and satellite platform information for each detected hotspot. This procedure prevented the double counting of fires by overlapping AQUA and TERRA satellite platforms.

Fire data were integrated monthly at the province level (Corrientes, Co; Misiones, Mi; Chaco, Ch; Santa Fe, SF and Entre Ríos, ER) and at the district level (103 districts corresponding to the five provinces). From these monthly satellite data, we also integrated the hotspots according to the following periods: Annual Growth Period Integration (ASI) from June$_{\text{year}}$ to July$_{\text{year + 1}}$ (2004–2005, 2005–2006 and 2006–2007), and Seasonal Integration (SI) (spring 2004–2007, summer 2004–2007, winter 2004–2007 and autumn 2004–2007). The integration from July to June (ASI) allows us to analyse the fire season continuously, unlike when the fires are integrated by calendar year from January to December. The SI, however, allows us to evaluate the periods most affected by fires and associate them with certain land-use practices, recreation activities or even to certain prevailing climatic conditions.

Land use/cover variables were extracted from the latest National Agricultural Census data available (*Censo Nacional Agropecuario*, CNA 2002) for the whole study area at district level (103 districts): (I) Total Cultivated Area (TC), including Total Crops (CR), Annual Crops Area (AC), Perennial Crops Area (PC), Cultivated Forage Area (CF), Perennial Forage Area (PF), Cultivated Forest Area (FO), and Other Crops Area (OC); and (II) Total Non-Cultivated Area (TNC) including grasslands (GR), Natural Forests (NFs), Marginal Area – non-capable/waste – (MA), Non-Used Area (NU) and Miscellaneous Area (MI). As productive variables at the district level, we analysed total number of cattle (heads), total number of sheep (heads), total number of goats (heads) and total livestock (heads). Even when we are comparing data from the 2002 Census with fire products for the period 2003–2007, we considered that no important changes were produced in the fraction of cultivated/non cultivated lands.

Precipitation (PP, mm yr^{-1}) and potential evapotranspiration (PET, mm yr^{-1}) data were obtained from INTA (*Instituto Nacional de Tecnología Agropecuaria*) meteorological stations located in the study area. Also, the relationship between PP and PET (PP/PET) was calculated in order to obtain an indicator of water availability (Thornthwaite and Mather 1957). These data were processed daily for the period analysed and then integrated to create monthly, seasonal and annual databases.

Taking into account the collected information (hotspots, land use/cover and climate data), a general descriptive analysis was done (Tukey 1977) and possible correlations and regressions between the variables were analysed.

3. Results

Mean annual integrated hotspot density for the whole study area was 0.05 hotspots km^{-2} yr^{-1} (0.06, 0.037 and 0.04 for 2004–2005, 2005–2006 and 2006–2007, respectively), corresponding to one fire per year for every 20 km^2. The density (and temporal variability) of fire hotspots varied significantly across provinces (F = 6.73, p = 0.00675) following the ranking Chaco > Misiones > Corrientes > Santa Fe > Entre Rios (0.066, 0.058, 0.04, 0.03 and 0.027 hotspots km^{-2} yr^{-1} respectively; figure 2(*a*)).

Hotspots were concentrated in two periods in most of the provinces analysed: a higher peak at the end of winter (maximum in August) and a smaller peak at late summer/early autumn (maximum in March; figure 2(*b*) and (*c*)). However, in Corrientes, the relative importance of these two peaks was inverse. The inter-annual variation of total hotspots integrated annually from $June_{year}$ to $July_{year+1}$ (ASI) was significantly and negatively associated with the mean water availability from $January_{year}$ to $June_{year}$ of the pre-fire season ($r^2 = 0.51$, $p < 0.05$; figure 3). This relationship between total hotspots ASI and the mean water availability was stronger in Chaco and Corrientes ($r^2 = 0.51$ and $r^2 = 0.40$ respectively), and in the years 2006–2007 and 2004–2005 ($r^2 = 0.54$ and $r^2 = 0.51$ respectively).

Among human and natural factors associated with fire occurrence, the proportion of uncultivated land was best related to it (table 1). When we evaluated only the best correlations, we observed that the summer and autumn fires were significantly and positively related to the total uncultivated area proportion ($r^2 = 0.32$ and $r^2 = 0.28$ respectively, $p < 0.05$). The grasslands under an extensive livestock production presented the same behaviour as the total uncultivated area ($r^2 = 0.38$ for summer hotspots, $p < 0.05$; and $r^2 = 0.37$ for autumn, $p < 0.05$). In the case of Misiones, a province characterized by high rainfall and a very large proportion of the total area covered by cultivated forests (e.g. *Pinus elliottii*, *Eucalyptus grandis*, *Pinus caribaea*, *Araucaria angustifolia*) or subtropical native rainforests (e.g. *Cedrela fissilis Vellozo*, *Tabebuia*, *Enterolobium contortisiliquum*, *Peltophorum dubium*) (Martínez-Carretero 1995), non-significant relationships were found between the land use/cover variables and fire occurrence. The same results were observed in the provinces of Chaco and Santa Fe, which are dominated by hardwood trees and grasslands respectively (Soriano and Paruelo 1992). In Entre Rios, the most cultivated province of the region, the mean annual hotspot density (hotspots km^{-2}) showed a significant positive relationship with marginal areas (non-capable or waste areas) of the territory

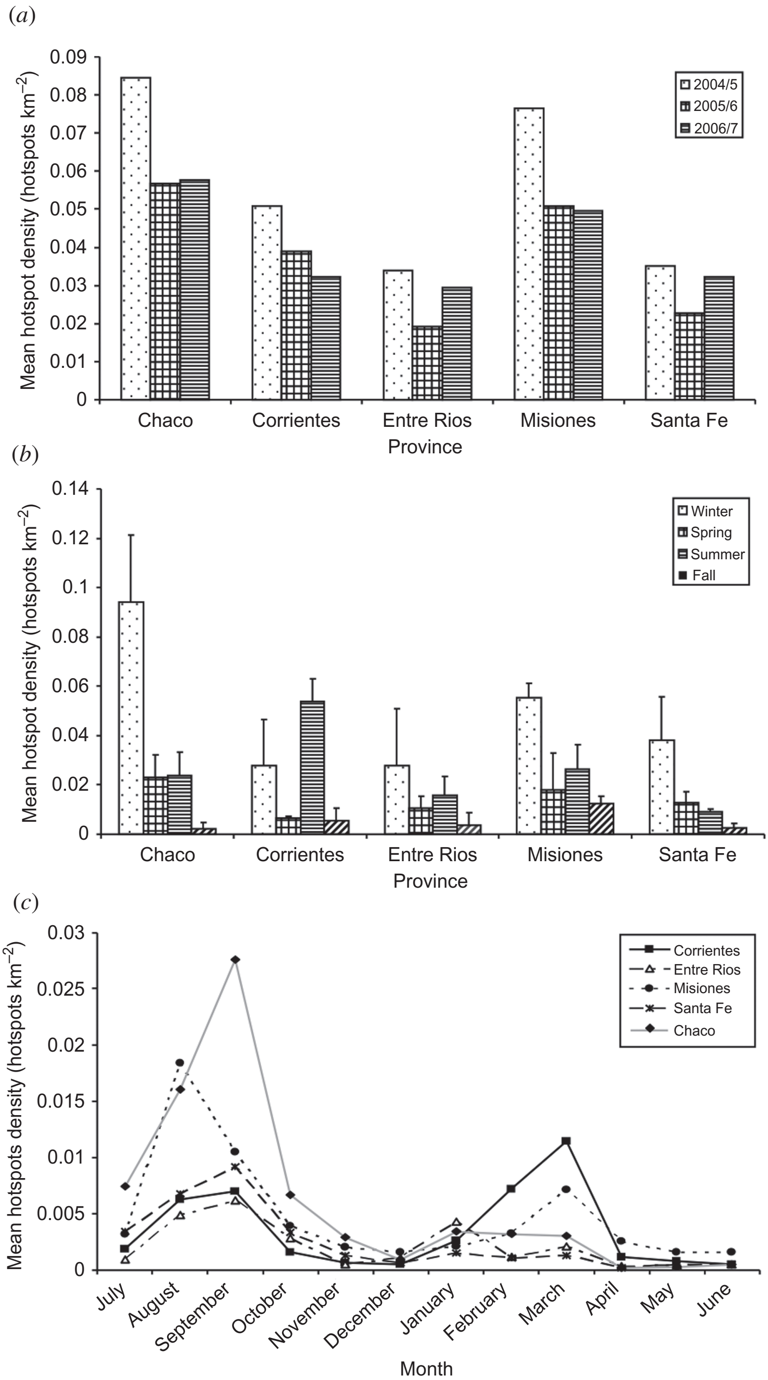

Figure 2. Mean hotspot density (hotspots per km^2) for the provinces of Chaco, Santa Fe, Misiones, Corrientes and Entre Rios. (*a*) Annual integration values (2004–2005, 2005–2006 and 2006–2007); (*b*) mean seasonal values (winter, spring, summer and autumn), errors bars represent the standard deviation of fires during the three years of study; (*c*) mean monthly values (January to December).

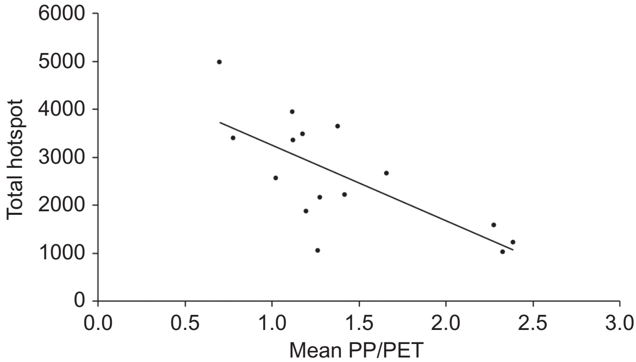

Figure 3. Relationship between total hotspots and mean PP/PET ratio. PP = rainfall (mm). PET = potential evapotranspiration (mm) ($y = -1573.8x + 4827.8$; $r^2 = 0.51$).

Table 1. Pearson product–moment correlation coefficients between hotspot and land use/cover types for the whole study area.

	Land use/cover														
Hotspots	TC	CR	AC	PC	CF	AF	PF	FO	OC	TNC	GR	NF	MA	NU	MI
Jan	0.00	0.05	0.03	0.14	0.04	0.05	0.03	0.01	0.17	*0.26	*0.29	0.02	0.14	*0.30	0.00
Feb	0.10	0.12	0.11	0.07	0.10	0.10	0.09	0.18	0.12	*0.27	*0.37	0.07	0.03	0.17	0.02
Mar	0.13	0.14	0.14	0.05	0.12	0.13	0.11	0.16	0.12	*0.23	*0.33	0.11	0.03	*0.24	0.09
Apr	0.06	0.08	0.15	*0.23	0.12	0.15	0.09	*0.47	0.06	*0.24	*0.28	0.03	0.11	*0.34	0.01
May	0.03	0.07	0.04	0.06	0.07	0.08	0.06	0.16	0.08	*0.44	*0.44	0.19	0.16	*0.30	0.07
Jun	0.05	0.02	0.06	0.00	0.04	0.07	0.02	0.11	0.14	*0.22	*0.22	0.08	0.07	0.16	0.02
Jul	0.03	0.06	0.07	0.11	0.04	0.03	0.03	0.03	0.11	*0.28	*0.25	*0.21	0.01	0.06	0.03
Aug	0.05	0.01	0.08	0.08	0.05	0.06	0.04	0.08	0.05	*0.25	*0.22	0.16	0.05	0.18	0.12
Sep	0.04	0.01	0.10	0.18	0.04	0.04	0.03	0.09	0.08	*0.27	*0.23	*0.21	0.02	0.15	0.08
Oct	0.07	0.02	0.12	0.13	0.01	0.01	0.00	0.07	0.06	*0.25	*0.22	0.18	0.05	0.15	0.07
Nov	0.06	0.07	0.08	0.09	0.01	0.02	0.00	0.00	0.02	0.14	0.09	0.13	0.02	0.17	0.04
Dec	0.09	0.01	0.11	0.06	0.00	0.01	0.03	0.04	0.09	*0.27	*0.24	0.14	0.14	*0.24	0.03
Spring	0.05	0.02	0.11	0.16	0.03	0.03	0.02	0.08	0.07	*0.26	*0.22	*0.20	0.02	0.15	0.07
Summer	0.04	0.09	0.03	0.12	0.07	0.08	0.06	0.10	0.16	*0.32	*0.38	0.01	0.11	*0.28	0.01
Autumn	0.12	0.14	0.14	0.01	0.12	0.14	0.11	*0.21	0.12	*0.28	*0.37	0.07	0.06	*0.28	0.08
Winter	0.05	0.02	0.08	0.09	0.05	0.05	0.03	0.04	0.08	*0.27	*0.24	0.18	0.04	0.13	0.08
JD_Mean	0.02	0.05	0.05	0.13	0.06	0.06	0.05	0.04	0.11	*0.32	*0.31	0.13	0.06	*0.24	0.07
JJ_Mean	0.02	0.05	0.05	0.12	0.06	0.06	0.04	0.04	0.10	*0.32	*0.31	0.15	0.07	*0.24	0.07

Notes: Total cultivated area (TC), total crops (CR), annual crops (AC), perennial crops (PC), cultivated forage (CF), perennial forage (PF), cultivated forest area (FO), other crops area (OC), total non-cultivated area (TNC), grasslands (GR), natural forests (NFs), marginal area – non-capable/waste – (MA), non-used area (NU) and miscellaneous area (MI). *Significant differences ($p < 0.05$; $n = 103$).

($r^2 = 0.74$, $p < 0.0001$; figure 4). In Corrientes, this significant relationship between fires and marginal areas was observed as well ($r^2 = 0.67$, $p < 0.0001$; figure 4).

For 103 districts, those in which the livestock and land use/cover data were available, we observed that a great part of the cattle activity is concentrated on non-cultivated lands (table 2), particularly in natural grasslands (Corrientes: $r^2 = 0.84$,

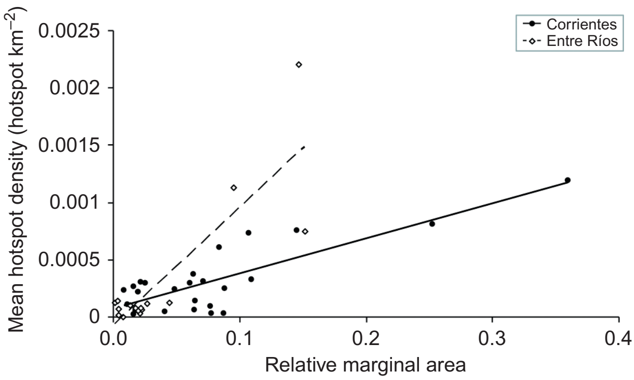

Figure 4. Relationship between mean annual hotspot density and the relative marginal area for the province of Entre Rios – dashed line – (r^2 = 0.74, p < 0.0001, n =17, y = –0.0000749540828 + 0.0103373197 × x) and Corrientes – full line – (r^2 = 0.67, p < 0.0001, n = 25, y = 0.0000747362095 + 0.00305195941 × x), by district.

Table 2. Pearson product–moment correlation coefficients between livestock (cattle, ships or goats heads) and land use/cover types for the whole study area.

	Livestock (heads)			
Land use/cover	Cattle	Sheep	Goats	Total
Total cultivated area	*0.49	0.10	0.06	*0.42
Total crops	*0.35	0.11	0.06	*0.27
Annual	*0.34	0.10	0.04	*0.29
Perennial	0.18	0.03	0.10	0.18
Forests	0.12	0.04	0.09	0.12
Others	0.07	0.03	*0.33	0.05
Total forages	*0.72	0.06	0.02	*0.64
Annual	*0.79	0.04	0.05	*0.71
Perennial	*0.65	0.06	0.05	*0.58
Total non-cultivated	*0.78	*0.37	*0.28	*0.80
Grasslands	*0.78	*0.46	0.01	*0.80
Natural forests	*0.37	0.04	*0.61	*0.38
Marginal areas	*0.34	0.03	0.02	*0.31
Non-used	*0.21	0.02	*0.32	*0.22
Miscellaneous	0.22	0.13	*0.53	0.24

*Significant differences (p < 0.05; n =103).

p < 0.05; Misiones: r^2 = 0.27, p < 0.05; and Santa Fe: r^2 = 0.5, p < 0.05) and natural forests (Chaco: r^2 = 0.85, p < 0.05; and Entre Ríos: r^2 = 0.5, p < 0.05). These areas were also the most affected by hotspots (table 2).

4. Discussion

Despite possible false detection, underestimation or overestimation of total burned areas (Dozier 1981, Kaufman and Justice 1998, Kaufman *et al.* 1998, Giglio *et al.* 1999, Li *et al.* 2001, Briess *et al.* 2003), remote sensing provides very valuable information for the recognition, planning, prediction and prevention of fires in high-risk natural environments like the ones presented in this work.

From basic and available information like the hotspot data, it is possible to link the temporal and spatial patterns of fires with additional variables to explain fire behaviour through time and space. In this work, we examined the inter- and intra-annual frequency of fires, their density by district and province and their relation to climate variables such as water availability. We also examined the relationship between land use and livestock variables with fire patterns in the study region.

Our results evidenced that a large part of the inter-annual variation of hotspots is associated with water availability during the previous growing season. This behaviour could be associated with the presence of a great biomass accumulation during that growing season (due to high water availability), that will represent a larger fuel quantity in the season with the highest frequency of fires. These kinds of relationships, which could be related to the presence of highly inflammable dead materials, seem to improve the current fire-danger indices generated for the region.

The study of the temporal patterns of fire occurrence showed that most grasslands burn at the end of the winter season. While this burning may promote the regrowth and growth of C_4 species in the spring–summer season, it may damage the growth of winter species (C_3), which cover a very important forage deficit in the annual balance of these livestock production systems. For this reason, many fire management experts suggest the possibility of applying controlled fires at the end of the growing season (March–May), increasing in this way the forage vegetation growing in the winter recess season.

It is important to highlight that agricultural expansion in Argentina is displacing livestock towards marginal areas dominated by natural vegetation (mainly grasslands and savannahs) where fires are commonly used as a management practice. The higher productive pressure on these ecosystems requires better programs and strategies of fire management.

Evidence from the previous discussion was observed during April 2008, when a great fire event affected around 70 000 ha in the Paraná River delta (south of Entre Rios and north of Buenos Aires provinces). In this region, where reliable fire information is scarce, the information obtained from remote sensing (monthly fire frequency) and the information about the livestock displacement towards marginal areas (caused by the agricultural surface increase) are available and easily interpretable. These data could be useful in order to design the correct pre-fire planning tasks (vegetal fuel reduction, creation of fire barrier, among others) and to reduce the fire damage caused to the environment and to the only available resource of forage.

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