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RESEARCH PAPER

Continental fire density patterns in South America

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ABSTRACT

Aims Quantification of the effects and interactions of natural and anthropogenic factors, including climate, canopy structure, land use and management conditions, on vegetation burning. The study of these relationships is fundamental to predict regional fire patterns and develop sound management and regulation policies for biomass burning at national and global levels.

Location Southern South America, including Argentina, Brazil, Paraguay, Uruguay, Bolivia and Chile.

Methods Based on National Oceanic and Atmosphere Administration–Advance Very High Resolution Radiometer (NOAA–AVHRR) satellite images, we identified fires in southern South America with a daily frequency for two periods (1999/2000 and 2000/01) using a contextual fire detection algorithm and integrating the density of these fires at a monthly scale into a $0.5 \times 0.5°$ grid. We combined vegetation and climate global databases and land use information from national census data to explore the relationship of these factors with fires across the region.

Results The whole study region had a mean fire density of 0.10 and 0.05 fires km^{-2} year^{-1} in 1999/2000 and 2000/01, respectively, with extreme values as high as 1.37 in fires km^{-2} year^{-1} in Para State, Brazil. Water deficit estimates, derived from a climatic water balance, showed the better correlation with fire density ($r = 0.28$; $P < 0.001$; $n = 4467$), interacting strongly with land use. In areas with low agricultural use fire density increased with water deficit, whereas in highly agricultural areas this relationship was not observed. Agriculture significantly reduced fire density in prairies and savannas but increased its frequency in rain forests.

Main conclusions These results suggest that agriculture prevents biomass burning in semiarid areas but enhances it in humid environments, where biomass accumulates at faster rates.

Keywords

Agricultural fires, fire occurrence, land cover changes, NOAA/AVHRR, remote sensing, water deficit.

INTRODUCTION

Biomass burning has a significant role in planetary energy balance and biogeochemical cycles, cloud formation and local and regional precipitation regimes (Crutzen & Andreae, 1990). It is also an important aspect of land ecosystem use, representing both a management tool and a degradation agent (Menaut *et al.*, 1993). Scientists, land managers and policy makers at both national and international levels require a better understanding of the magnitude of fire activity, its spatial and temporal distribution and factors affecting its occurrence in order to predict and regulate its impact on climate and atmospheric composition, as well as on land productivity, management practices and environmental degradation.

Fire occurrence is influenced by biophysical as well as human factors. How the frequency and distribution of fires, as well as their ignition agents, vary with climatic and meteorological conditions (amount and seasonal distribution of precipitation

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or relative humidity), vegetation type and water status or land use has been documented in the literature (Andreae, 1992; Cahoon *et al.*, 1992; Larsen, 1996; Gonzalez-Alonso *et al.*, 1997; Kitzberger & Veblen, 1997; Dwyer *et al.*, 2000; França & Setzer, 2001). Regarding human influences, palaeo-records demonstrate that for more than 1 million years people have been altering the natural patterns of fire occurrence intensity and frequency (Levine, 1991; Andreae, 1992; Kitzberger & Veblen, 1997). Humans can set fires accidentally or for particular purposes, such as deforestation and land preparation for agriculture, weed and pest control, restriction of fuel accumulation or larger-scale burning, improved access for hunting or energy provision (Andreae, 1992).

Remote sensing, through the detection of hot spots of high surface temperature, allows consistent monitoring of vegetation burning patterns at different spatial and temporal scales (Cahoon *et al.*, 1992; Justice & Dowty, 1994; Nelson, 1994; Barbosa *et al.*, 1999; Dwyer *et al.*, 2000). The detection is usually based on the emission response of fires in the infrared (IR) portion of the electromagnetic spectrum, principally in the middle IR (3–5 μm) and the thermal IR (10–14 μm) bands. From measurements at these wavelengths, fire is detected at both regional and continental scales through the classification of pixels applying various algorithms to the spectral data. This approach has yielded maps of active fires (hot spots) based on different satellite platforms and sensors, such as the National Oceanic and Atmosphere Administration–Advance Very High Resolution Radiometer (NOAA–AVHRR) (e.g. Eva & Flasse, 1996), Along Track Scanning Radiometer (ATSR) (e.g. Eva & Lambin, 1998), Moderate Resolution Imaging Spectroradiometer (MODIS) (Giglio *et al.*, 2003), Geostationary Operational Environmental Satellite (GOES) (e.g. Prins & Menzel, 1994) and the Defense Meteorological Satellite Program (DMSP) (e.g. Cahoon *et al.*, 1992) satellites, among others.

Continental-scale approaches to active fire occurrence offer the opportunity to encompass broad gradients of climate, vegetation and land use, helping to understand their role in determining fire activity. Our objective was to explore the interactions between biophysical and human factors shaping fire patterns at the continental scale based on NOAA–AVHRR satellite data and focusing on abiotic (climate), biotic (vegetation) and human (land use and management) variables. We focused on the Mercosur countries in South America (Argentina, Bolivia, Brazil, Chile, Paraguay and Uruguay), an area that extends over 60 degrees of latitude and that encompasses a broad range of climatic, vegetation and land-use patterns.

MATERIALS AND METHODS

We explored active fire patterns for Brazil, Argentina, Paraguay, Uruguay, Bolivia and Chile applying a fire detection algorithm to NOAA–AVHRR images throughout the period August 1999–April 2001. Fire information was associated with climate, vegetation and land use information derived from global databases and national census data.

Fire density (FD) maps were provided through the World Fire Web Project (WFW) (Stroppiana *et al.*, 2000). These maps integrated NOAA–14 AVHRR afternoon passes of 1.2 km^2 spatial resolution from overlapping scenes acquired by two receiving stations. The images were processed with a contextual active fire detection algorithm (Prins & Menzel, 1992; Justice & Dowty, 1994; Flasse & Ceccato, 1996) for both years. This two-stage algorithm used information from AVHRR channels 3 (3.55–3.93 μm) and 4 (10.3–11.3 μm) corresponding to the top of the atmosphere brightness temperature for middle infrared and thermal infrared, respectively. Alternative fire detection tools have been developed, for example, by INPE/CPTEC, Brazil (fire group: www.cptec.inpe.br).

We used data obtained from antennas in Campinas, Brazil (46°37′12″ W, 23°34′48″ S) and Buenos Aires, Argentina (58°40′09″ W, 34°36′30″ S) for the areas stated in Fig. 1 corresponding to daytime images (i.e. afternoon, ascending passes only). Daily images corresponding to May and July 2000 were excluded from the analysis due to radiometric noise caused by high latitude–low solar elevation angle interactions for the southern portion of the study (Patagonia in Argentina and Chile). Also excluded were the overlapping areas of both antennas. We characterized the density of fire pixels (FD) based on

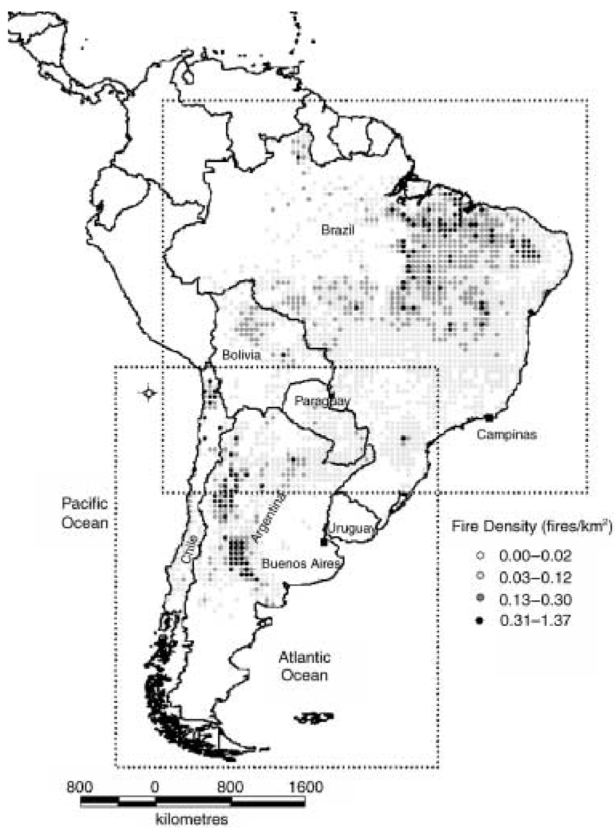

Figure 1 Mean fire density (FD: fires km^{-2}) for the period August 1999–April 2001. Square dashed lines represent the satellite image coverage areas of Campinas (Brazil) and Buenos Aires (Argentina) antennas.

Table 1 Fire density (FD: fires km^{-2}) for different biomes of South America for low and high intensity agricultural conditions. n = Number of samples (cells of 0.5° × 0.5°); SE = standard error. (***) = significant difference ($P < 0.001$) between low and high agriculture proportion (ANOVA analysis)

	Low agriculture (< 0.2% agriculture)			High agriculture (> 30% agriculture)		
Biome	Mean (fires km^{-2})	n	SE (fires km^{-2})	Mean (fires km^{-2})	n	SE (fires km^{-2})
Dry tropical forest	0.255	179	0.020	0.267	550	0.010
Grassland steppe	0.217	214	0.021	0.202	60	0.046
Prairies	0.125***	41	0.014	0.022	184	0.002
Rain forest	0.075***	1058	0.005	0.196	366	0.013
Savannas	0.402***	164	0.025	0.280	684	0.008

monthly integrations within 0.5 × 0.5° cells using the normalized fire count (NFC), which is calculated as follows:

$$\mathrm{NFC} = \frac{\mathrm{AFC} * \cos(\mathrm{latitude}) * 30 * 2500}{(\mathrm{ESP} - \mathrm{CP})},$$

where AFC is the actual fire count (fire pixels) for all the NOAA–AVHRR sensor data within a 0.5 × 0.5° cell in all the available scenes of a month, cos(latitude) is an area adjustment factor for the cell latitude, 2500 is the number of NOAA–AVHRR pixels per grid cell at the equator, 30 is the number of days per month, ESP (effectively screened pixels) is the sum of NOAA–AVHRR pixels that fire presence was detected in all the scenes within a month for a given grid cell and CP (cloudy pixels) is the number of pixels covered by clouds. In this manner, the NFC allowed adjustment of the number of actual observed fires on an equal area and screening intensity basis.

Climatic variables, such as mean monthly values of temperature (°C) or precipitation (mm), were derived from the IIASA database (Leemans & Cramer, 1990). From this database, we computed mean potential evapotranspiration (PET) and actual evapotranspiration (AET) for each grid cell using a water balance approach (Thornthwaite & Mather, 1957). We calculated the mean annual water deficit (WD) as the integral of the mean monthly difference between PET and precipitation. Vegetation cover of each grid cell was obtained from biome maps with 25 km^2 resolution derived from a modification of Hueck and Seibert's (1972) original maps (Paruelo *et al.*, 2004). A total of 11 classes (major biomes) was extracted from the database: deserts (De), shrub steppes (SS), prairies (Pr), wetlands (We), savanna (Sa), grass steppes (GS), dry temperate forests (DteF), humid temperate forests (HteF), dry tropical/subtropical forests (DtrF), rain forests (RF) and humid tropical/subtropical forests (HtrF). Among them, the most frequent in the study area (see Table 1) could be described as: DtrF: a forest with more than 3 months of dry season; GS: an herbaceous cover between 10 and 40% with a clear dry season and a shrub canopy cover less than 20%; P: an herbaceous cover greater than 40%; RF: tree canopy cover greater than 70% and height greater than 5 m with a dry season of less than 1 month; and Sa: mainly as a tropical grassland with 10–20% shrubs (e.g. the Brazilian cerrado).

For each grid cell we computed the contribution of each biome type. Grid cells in which a single biome represented more than 80% were considered 'pure' and used to explore biome-type effects. National census data for each country covering the period 1997–2001 were used to link FD to land use. In Argentina, census data were integrated for 23 provinces (INDEC, 2000/01), in Brazil for 22 states (IGBE, 2000/01), in Chile for 12 regions (INE, 1999/2000) and in Paraguay for 17 provinces (DGEEC, 1997/98). For each country and political subdivision, except for Uruguay, we obtained the total and cultivated area (km^2). For the analysis we considered either low (< 0.2%) or high (> 30%) levels of agriculturalization. This selection yielded 35 'non-agricultural' and 11 'agricultural' polygons (administrative levels).

For the analyses involving climate and vegetation information we used individual grid cells (4717 cells including Brazil, Argentina, Paraguay, Uruguay, Bolivia and Chile). Due to unreliable fire detection in desert areas of western Argentina and northern Chile, associated with areas of hot soils and bright surfaces (Stroppiana *et al.*, 2000), 117 grid cells were discarded. To analyse the association of FD to land use data, we integrated FD data at the administrative level (46 polygons ranging between 2900 km^2 and 1,570,000 km^2).

RESULTS AND DISCUSSION

In total, 1,434,160 and 639,265 fires for the whole study area during the periods 1999/2000 and 2000/01, respectively, were detected. Brazil and Argentina, the biggest countries of the region in terms of surface, concentrated 84% of the total fires (63 and 21%, respectively), followed by Bolivia 6%, Paraguay 6% and Chile 4%. In Uruguay, in particular, the number of fires was negligible. A 14% and 5% fraction of the total study area had at least one fire in each period, respectively. Similar percentages of affected areas (*c.* 6% of the total area) were obtained by Dwyer *et al.* (2000) for the world during the period 1992/93 also using NOAA–AVHRR image data.

Fires spread all around the continent from latitude 5° N in the north of Brazil to 48° S in Patagonia (Argentina). FD ranged between 0 and 1.37 detected fires km^{-2} during both periods (Fig. 1, Appendix S1 in Supplementary Material). The minimal values, 0 fires km^{-2}, were observed in Buenos Aires Province,

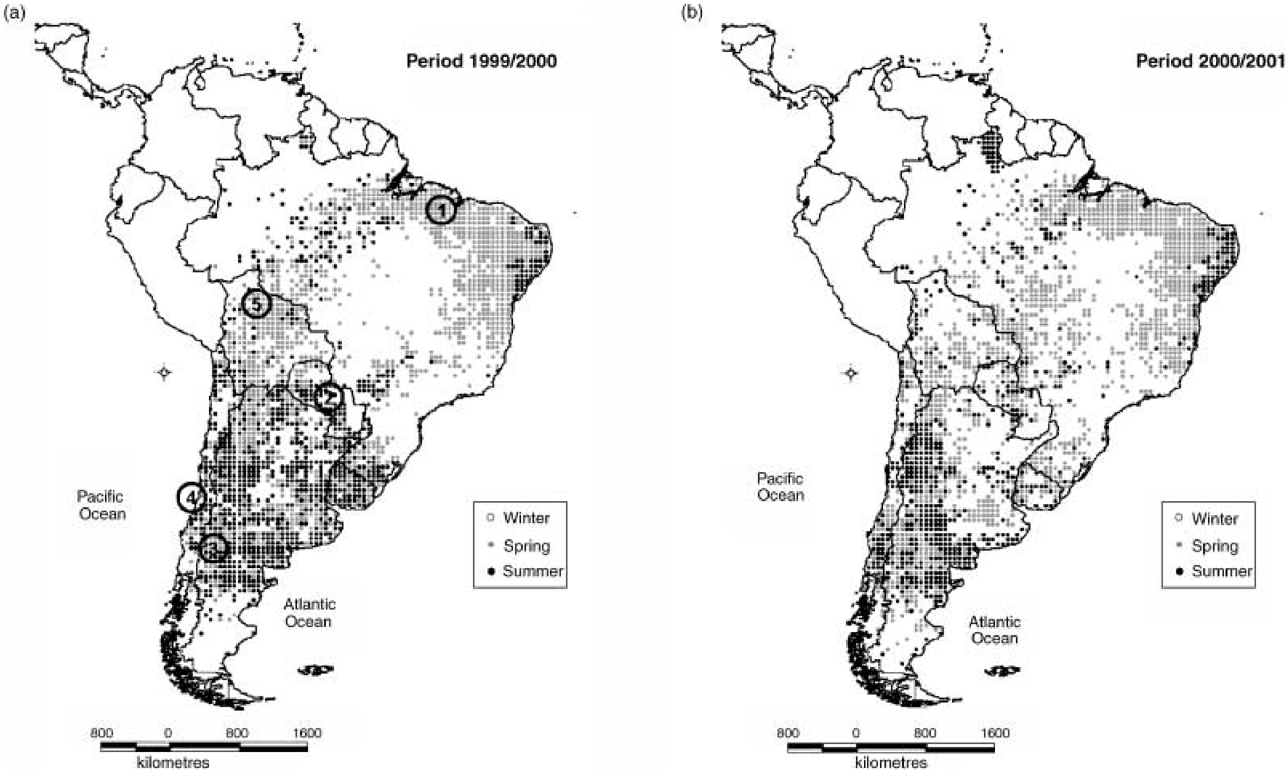

Figure 2 Month of maximum fire density (FD: fires km^{-2}) for the period (a) August 1999–April 2000 and (b) August 2000–April 2001. The circled numbers correspond to the areas described in Fig. 3.

Argentina (60° W, 37° S) during both the periods studied, or in Uruguay. The state of Para (54° W, 5° S) in Brazil registered the maximal values of FD (1.37 fires km^{-2}) during the period 1999/2001. It is important to highlight that although fire activity during 1999/2000 was greater than in 2000/01, statistical analysis yielded identical results in terms of total detected fire pixels, considering each growing season independently or the period as a whole. Craig *et al.* (2002), using the same satellite images and detection algorithms, reported FD values in Australia between 0 and 1.42 fires km^{-2} during the period 1999/2000. However, the total numbers of fires detected during that period were significantly lower in Australia than in southern South America (230,046 vs. 1,434,160 fires year^{-1}, respectively). Considering the total number of fires year^{-1} with total area (7,686,850 km^2 for Australia and 13,717,355 km^2 for southern South America), 0.03 fires km^{-2} year^{-1} were detected in Australia and 0.10 fires km^{-2} year^{-1} in southern South America.

Both annual periods showed that most of the fires in southern South America occurred during late winter and spring (August–December) (Fig. 2a,b, Appendix S2a,b in Supplementary Material). FD during summer and early autumn (January–April) represented 26% and 19% of the annual total in 1999/2000 and 2000/01, respectively. At the country level, Brazil fires spread in spring following a progression SW–NE from August to December [Figs 2a,b and 3(i)]. In Paraguay and Bolivia, detected fires were dominant during spring [Figs 2a,b and 3(ii) and (v), respectively], while in Chile fires were more frequent in the summer [Figs 2a,b and 3(iv)]. Argentina presented an intermediate situation, with spring fires in the north and summer fires in the W–SW (semiarid region) [Figs 2a,b and 3(iii)]. These results agreed with seasonal patterns obtained by Dwyer *et al.* (1999 and 2000) for the South American continent during the period 1992/93. In Australia, Craig *et al.* (2002) also found spring fires in the northern portion of the country (the same latitude as central Brazil) and summer fires in more southerly latitudes (the same latitude as central Argentina).

Climatic diagrams (Walter & Lieth, 1960) in Fig. 3 provide some evidence for environmental controls on FD. For example, in Maranhao (Brazil) [Fig. 3(i)], water deficiencies during the period July–September are in accordance with the occurrence of fires during August–October in both years. In Coquimbo (Chile) [Fig. 3(iv)], climatic deficits during September–March could explain fires from October to February. Among climatic variables, mean annual water deficit showed the highest correlation with FD over the continent throughout both study years ($r = 0.28$; $P < 0.001$; $n = 4467$). FD increased with water deficit for both high and low agriculturalization areas (Fig. 4). However, both agriculturalization levels differed significantly in their FD for the different water deficit levels. In areas with a lower water balance (< 200 mm year^{-1}), agricultural areas (> 30% of agriculturalization) had twice as many fires as non-agricultural areas (< 0.2% of agriculturalization). At intermediate water deficits (200–300 mm year^{-1}), highly cultivated areas maintained higher mean fire densities than less cultivated areas, but with

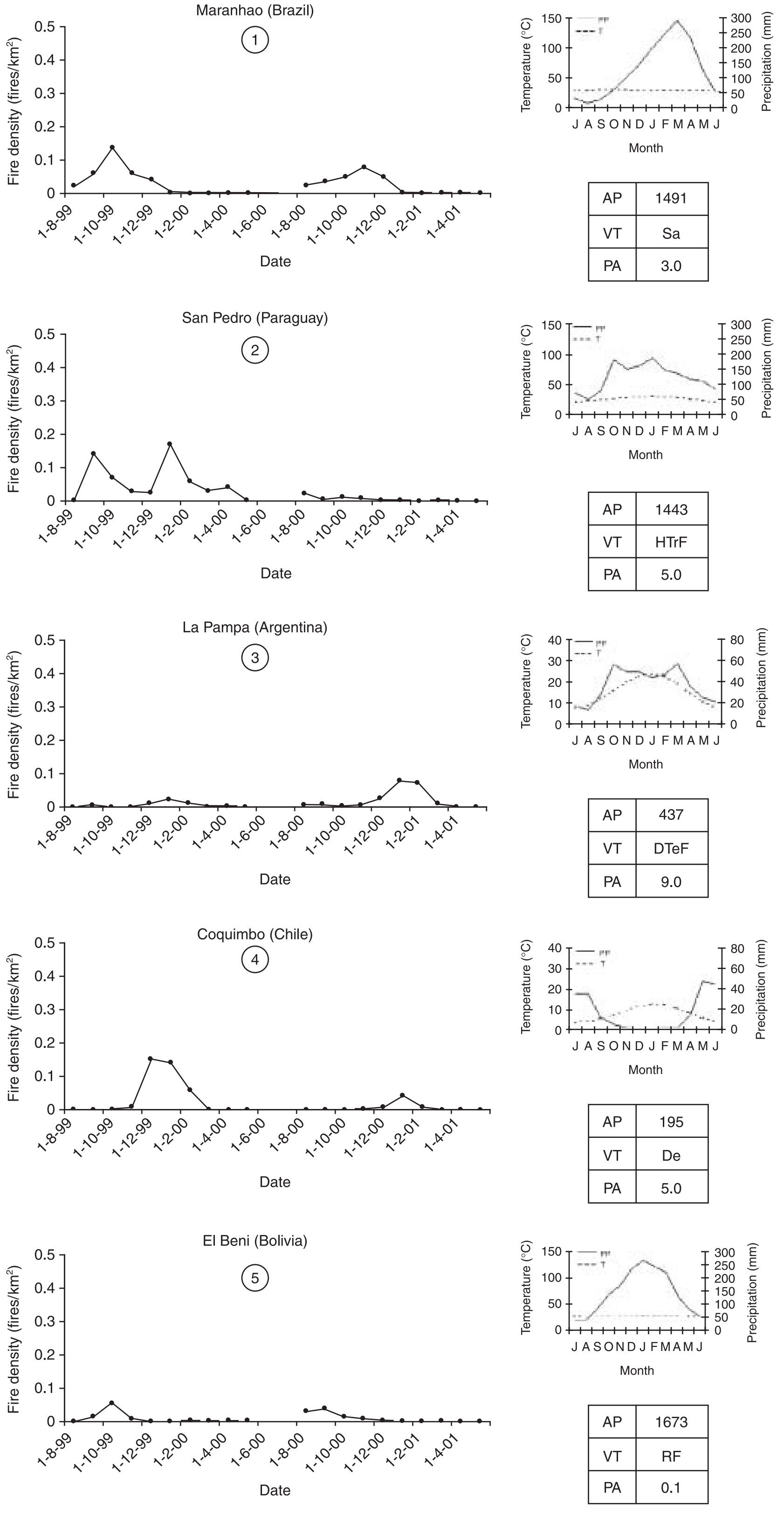

Figure 3 Seasonal fire density (fires km^{-2}) for six study areas: (i) Maranhao (Brazil), (ii) San Pedro (Paraguay), (iii) La Pampa (Argentina), (iv) Coquimbo (Chile) and (v) El Beni (Bolivia). See Fig. 2 for location of each area (150×50 km^2). A climatic diagram is presented for each study area. PP = mean monthly precipitation (mm); T = mean monthly temperature (°C). Water deficit is assumed when T values are higher than PP values. AP = mean annual precipitation (mm $year^{-1}$). VT = dominant biome (Sa = Savanna, HTrF = humid tropical forest, DteF = dry temperate forest, De = desert and RF = rain forest). PA = percentage of agriculture (%).

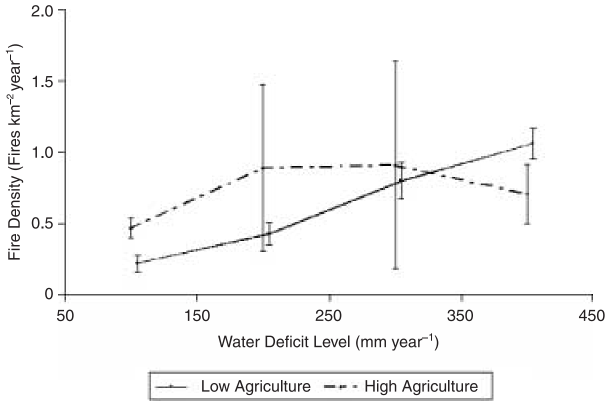

Figure 4 The relationship between mean water deficit (mm year^{-1}) and fire density (fires km^{-2} year^{-1}) for areas of low agricultural activity (solid lines) and areas of high agricultural activity (dashed lines). Water deficit levels correspond to: 1 = 0–99 mm; 2 = 100–199 mm; 3 = 200–299 mm; and 4 = greater than 300 mm. Low agricultural areas = less than 0.2% agriculture. High agricultural areas = more than 30% agriculture of the total area. Y-bars = ±95% confidence limits of mean.

higher variability. Agricultural zones with water deficit greater than 300 mm year^{-1} showed lower FD than non-agricultural areas (Fig. 4). These results are in accordance with the model proposed by Oesterheld *et al*. (1999), in which areas with a precipitation range of 450–700 mm and low primary productivity limited by low soil water and high lignin content of the litter sets the stage for high fire frequency.

Vegetation type influenced FD and showed interactions with land use ($P < 0.001$; $n = 3500$). Savannas, dry tropical forests and grassland steppes had the highest fire densities, whereas prairies and rain forests had the lowest fire densities (Table 1). In dry tropical forests and grassland steppes, FD showed no association with agricultural intensity. In savannas and prairies FD was lowest in areas with a high proportion of agriculture, whereas the opposite occurred in rain forests. A particular situation was observed in Uruguay, where 90% of the country is occupied by grasslands, and even when fires are used to improve pasture quality the detected number was insignificant. Spontaneous and intentionally caused fires in dry forests and steppes are probably favoured by the combination of dry conditions during part of the year (water deficit) and enough moisture supply to achieve a critical fuel accumulation for combustion. Regardless of agricultural dominance, these systems tend to have frequent fires. In savannas and prairies, agriculture may suppress fires through farming operations that base their weed/residue management on the use of machinery and herbicides rather than on fire (Dinerstein *et al*., 1995; Viglizzo *et al*., 2001). In contrast, the rain forest biome hosts principally subsistence agriculture schemes (FAO, 1997) in which economic and ecological conditions impose fire as a cheap and effective tool for land clearing, nutrient recycling and plant disease or weed control (Lanly, 1985; Achard *et al*., 2002).

CONCLUSIONS

Our work provides a baseline description of the patterns of fire occurrence at the continental scale suggesting strong causal interactions between climate and human activities, reproducing results that have been obtained widely at more local or regional scales (e.g. Diaz-Delgado *et al*., 2004). Across this region, agricultural activities were associated with fire prevention/restriction in semi-arid areas but promotion in humid environments, probably as a result of contrasting biomass accumulation patterns and removal needs by farmers. Policy approaches to fire regulation/control should acknowledge this interaction, adapting rules to local situations and focusing enforcement on those areas where fast ongoing agricultural expansion is most likely to increase fire occurrence, i.e. in the humid forests. Further development of continental (and potentially global) relationships between FD and climate, vegetation and land use/cover could be the basis to incorporate the feedbacks of land cover and climate changes on carbon emissions due to biomass burning in the global models of carbon dynamics. In this sense, the UN Framework Convention on Climate Change and its Kyoto Protocol (UNFCCC, 1997) have precise indications about the limitation of greenhouse gas emissions due to biomass burning.

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REFERENCES

Achard, F., Eva, H.D., Stibig, H.J., Mayaux, P., Gallego, J., Richards, T. & Malingreau, J.-P. (2002) Determination of deforestation rates of the world's humid tropical forests. *Science*, **297**, 999–1002.

Andreae, M.O. (1992) Biomass burning: its history, use, distribution and its impact on environmental quality and global climate. *Global biomass burning, atmospheric implications and biospheric implications* (ed. by J.C. Levine), pp. 3–21. MIT Press, Cambridge, MA.

Barbosa, P., Stroppiana, D., Grégoire, J.-M. & Pereira, J.M.C. (1999) An assessment of fire in Africa (1981–1991): burnt areas, burnt biomass and atmospheric emissions. *Global Biogeochemical Cycles*, **13**, 933–950.

Cahoon, D.R. Jr, Stocks, B.J., Levine, J.S., Cofer, W.R. III & O'Neill, P.O. (1992) Seasonal distribution of African savanna fires. *Nature*, **359**, 812–815.

Craig, R., Heath, B., Raisbeck-Brown, N., Steber, M., Marsden, J. & Smith, R. (2002) The distribution, extent and seasonality of large fires in Australia, April 1998–March 2000, as mapped from NOAA–AVHRR imagery. *Australian fire regimes: contemporary patterns (April 1998–March 2000) and changes since European settlement* (ed. by J. Russell-Smith, R. Craig, A.M. Gill, R. Smith and J. Williams). Australia State of the Environment Second Technical Paper Series (Biodiversity), Department of the Environment and Heritage, Canberra. pp. 1–77. Available at: http://www.ea.gov.au/soe/techpapers/index.html (accessed 2 January 2006).

Crutzen, P. & Andreae, M. (1990) Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. *Science*, **250**, 1669–1678.

Diaz-Delgado, R., Lloret, F. & Pons, X. (2004) Spatial patterns of fire occurrence in Catalonia, NE Spain. *Landscape Ecology*, **19**, 731–745.

Dinerstein, E., Olson, D.M., Graham, D.J., Webster, A.L., Primm, S.A., Bookbinder, M.P. & Ledec, A. (1995) *Conservation assessment of the terrestrial ecoregions of Latin America and the Caribbean.* The World Wildlife Fund, The World Bank, Washington, DC, USA.

Dwyer, E., Pereira, J.M.C., Grégoire, J.-M. & DaCanara, C.C. (1999) Characterization of the spatio-temporal patterns of global fire activity using satellite imagery for the period April 1992 to March 1993. *Journal of Biogeography*, **27**, 57–69.

Dwyer, E., Pinnock, S., Grégoire, J.-M. & Pereira, J.M.C. (2000) Global spatial and temporal distribution of vegetation fire as determined from satellite information. *International Journal of Remote Sensing*, **21**, 1289–1302.

Eva, H. & Flasse, S. (1996) Contextual and multiple-threshold algorithms for regional active fire detection with AVHRR data. *Remote Sensing Reviews*, **14**, 333–351.

Eva, H. & Lambin, E.F. (1998) Burn area mapping in central Africa using ATSR data. *International Journal of Remote Sensing*, **19**, 3473–3497.

Flasse, S.P. & Ceccato, P.S. (1996) A contextual algorithm for AVHRR fire detection. *International Journal of Remote Sensing*, **17**, 419–424.

Food and Agricultural Organization (FAO) (1997) *State of the world's forests*. Food and Agriculture Organization of the United Nations, Rome, Italy.

França, H. & Setzer, W. (2001) AVHRR analysis of a savanna site through a fire season in Brazil. *International Journal of Remote Sensing*, **22**, 2449–2461.

Giglio, L., Descloitres, J., Justice, C.O. & Kaufman, Y. (2003) An enhanced contextual fire detection algorithm for MODIS. *Remote Sensing of Environment*, **47**, 1311–1318.

Gonzalez-Alonso, F., Cuevas, J.M., Casanova, J.L., Calle, A. & Illera, P. (1997) A forest fire risk assessment using NOAA–AVHRR images in the Valencia area, eastern Spain. *International Journal of Remote Sensing*, **18**, 2201–2207.

Hueck, K. & Seibert, P. (1972) *Vegetationskarte von Südamerika*. Gustav Fisher Verlag, Stuttgart.

Justice, C. & Dowty, P. (eds) (1994) *IGBP-DIS satellite fire detection algorithm workshop technical report*. IGBP-DIS working paper no. 9, p. 88, February 1993. NASA/GSFC, Greenbelt, MD.

Kitzberger, T. & Veblen, T.T. (1997) Influences of humans and ENSO on fire history of *Austrocedrus chilensis* woodlands in northern Patagonia, Argentina. *Ecoscience*, **4**, 508–520.

Lanly, J.P. (1985) Defining and measuring shifting cultivation. *Unasylva*, **37**, 17–21.

Larsen, C.P.S. (1996) Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1989. *The Holocene*, **6**, 449–456.

Leemans, R. & Cramer, W.P. (1990) *The IIASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid*. Working Paper WP-90-41. International Institute of Applied Systems Analysis, Laxenburg, Austria.

Levine, J.S., ed. (1991) *Global biomass burning: atmospheric, climatic, and biospheric implications*. MIT Press, Cambridge, MA.

Menaut, J.C., Abbadie, L. & Vitousek, P.M. (1993) Nutrient and organic matter dynamics in tropical ecosystems. *Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires* (ed. by P.J. Crutzen and J.G. Goldammer), pp. 215–231. Environmental Sciences Research Report, 13. Wiley, Chichester.

Nelson, B.W. (1994) Natural forest disturbance and change in the Brazilian Amazon. *Remote Sensing Reviews*, **10**, 105–125.

Oesterheld, M., Loreti, J., Semmartin, M. & Paruelo, J.M. (1999) Grazing, fire and climate effects on primary productivity of grasslands and savannas. *Ecosystems of disturbed ground* (ed. by L.R. Walker), pp. 287–306. Elsevier, New York.

Paruelo, J.M., Garbulsky, M.F., Guerschman, J.P. & Jobbágy, E.G. (2004) Two decades of Normalized Difference Vegetation Index changes in South America: identifying the imprint of global change. *International Journal of Remote Sensing*, **25**, 2793–2806.

Prins, E.M. & Menzel, W.P. (1992) Geostationary satellite detection of biomass burning in South America. *International Journal of Remote Sensing*, **13**, 2783–3462.

Prins, E.M. & Menzel, W.P. (1994) Trends in South American biomass burning detected with the GOES visible infrared spin scan radiometer atmospheric sounder from 1983 to 1991. *Journal of Geophysical Research*, **99**, 16719–16735.

Stroppiana, D., Pinnock, S. & Grégoire, J.-M. (2000) The Global Fire Product: daily fire occurrence, from April 1992 to December 1993, derived from NOAA–AVHRR data. *International Journal of Remote Sensing*, **21**, 1279–1288.

Thornthwaite, C.W. & Mather, J.R. (1957) Instructions and tables for computing potential evapotranspiration and the water balance. *Publications in Climatology*, **10**, 185–311.

United Nations Framework Convention on Climate Change (UNFCCC) (1997) Third session of the conference of the Parties to the UNFCCC in Kyoto, Japan (11 December 1997).

Viglizzo, E.F., Lértora, F.A., Pordomingo, A.J., Bernardos, J., Roberto, Z.E. & Del Valle, H. (2001) Ecological lessons and applications from one century of low external-input farming in the pampas of Argentina. *Agriculture, Ecosystems and Environment*, **81**, 65–81.

Walter, H. & Lieth, H. (1960–1967) Klimadiagramm-Wetatlas (World atlas of climatic diagrams). Veb. GustavFischer Verlag Jena, Germany.

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SUPPLEMENTARY MATERIAL

The following material is available online at www.blackwell-synergy.com/loi/geb

Appendix S1 Mean fire density (FD: fires km^{-2}) for the period August 1999–April 2001 (in colour).

Appendix S2 Month of maximum fire density (FD: fires km^{-2}) for the period (a) August 1999–April 2000 and (b) August 2000–April 2001 (in colour).