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Fire impacts on vegetation in Central Africa: a remote-sensing-based statistical analysis

Gabriela Bucini, Eric F. Lambin *

Department of Geography, Université catholique de Louvain, Place Louis Pasteur 3, B-1348 Louvain-la-Neuve, Belgium

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Abstract

The objectives of this study were to understand the role of fires on land-cover changes, and conversely the role of vegetation cover as a controlling factor of fires. The study, which was conducted in a region at the savannah/forest transition in the southwestern part of the Central African Republic, explores the differential impact on land cover of early- and late-season fires and analyses burning regimes as a function of human use of the land. This was addressed using multivariate regression models between maps of land-cover change derived from remote sensing data, maps of burnt areas and a detailed map of ecotypes. In dense forests, burning is strongly associated with land-cover changes, while in savannahs the occurrence of (mostly) early fires does not lead to land-cover change. Fires associated with continuous and fragmented burnt patches have similar impacts on vegetation cover. Dense semi-humid forests in the study area were affected by a high level of burning due to land uses at their peripheries. The results confirm recent findings concerning human control on the timing of burning in savannahs. Early fires fragment the landscape and prevent the spatial diffusion of later damaging fires. Where no human settlements are present, late fires become more prevalent. Finally, the study measured an increase in vegetation cover in a few areas affected by very early burning. Using burnt area rather than active fire data allowed a better analysis of the spatial association between landscape attributes and burning events. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Biomass burning; Central Africa; Fire; Land-cover change; Landscape fragmentation; Remote sensing; Savannah; Tropical forest

* Corresponding author. Tel.: +32-10-474477; fax: +32-10-472877.
E-mail address: lambin@geog.ucl.ac.be (E.F. Lambin).

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Introduction

Fires have been taking place throughout tropical savannahs and forests for millennia (Goldammer, 1990; Levine, 1991, 1996; Crutzen & Goldammer, 1993). As a landscape disturbance, fires result in partial or complete destruction of vegetation cover (Guerra, Puig, & Chaume, 1998), the impact of biomass burning largely depending on ecosystem type (Eva & Lambin, 2000). In dense humid forests, the presence of fires is usually associated with forest clearing, while savannah vegetation is resilient to fires, thanks to well-adapted species. In savannahs, the main short-term impact of fires is to prevent the replacement of herbaceous strata by woody biomass and to enhance the production of some graminaceous species (Menaut, 1993). Fires may also induce long-term changes in vegetation cover through their impact on soil nutrients, particularly through pyrodenitrification (Crutzen & Andreae, 1990). The two-way relationship between land-cover change and biomass burning still needs to be investigated in a systematic way.

In two previous studies, Ehrlich, Lambin, and Malingreau (1997) and Eva and Lambin (2000) analysed the spatial correlation between fires and land-cover change at, respectively, the regional and landscape scales. While the first study suffered from the high level of spatial aggregation of the data and the broad scale of the study, the second relied on maps of active fires, which are known to represent only a small and biased sample of biomass burning events (Eva & Lambin, 1998a,b). In the present study, the issue of interactions between fires and land-cover change is revisited at the landscape scale, using data of medium spatial resolution to measure land-cover change and using maps of burnt areas rather than maps of active fires to characterize biomass burning. Eva and Lambin (1998) have shown that burnt scars carry a 'memory' of previous burning events, remaining detectable for up to three weeks following a fire. They also have a good spectral separability on remotely sensed images. Burnt areas can therefore be reliably mapped by satellite sensors with a high temporal frequency of acquisition. Maps of burnt areas are much more representative of actual burning events than are maps of active fires, and allow for a detailed representation of the spatial pattern of burning. This can thus be related to spatially explicit data on vegetation distribution and land-cover change at a fine level of aggregation.

The objective of this study was to understand the role of fires on land-cover changes, and conversely the role of vegetation cover as a controlling factor of fires. This is addressed through the analysis, using multivariate regression models, of spatial associations between maps of burnt areas, a detailed map of ecotypes and maps of land-cover change derived from remote sensing data. In particular, the study explores the differential impact on land cover of early- and late-season fires, and analyses burning regimes as a function of human use of the land. The research was conducted in a Central African region at the savannah/forest transition in an area that comprises part of the International Global Atmospheric Chemistry EXPRESSO campaign (Experiment for Regional Sources and Sinks of Oxidants), which took place in November and December 1996 (Delmas et al., 1999).

Background

Fire is used for hunting, clearing land for agriculture, maintaining grasslands, controlling pests, and removing dry vegetation and crop residues to promote agricultural productivity and facilitate displacements (Hough, 1993; Bruzon, 1994). It can also be used as a tool for forest cover conversion (Fujisaka, Bell, Thomas, Hurtado, & Crawford, 1996; Nelson & Irmão, 1998) or can affect moist forests under exceptionally dry weather conditions or after selective logging has been undertaken (Holdsworth & Uhl, 1997; Nepstad et al., 1997), leading to forest degradation (Nepstad et al., 1999). Dry forests are more frequently affected by fire (Swaine, 1992). Fires also maintain savannah ecosystems by preventing the invasion of woody species, especially in forest/savannah transition zones (Furley, Proctor, & Ratter, 1992; Menaut, 1993; King, Moutsinga, & Doufoulon, 1997). Rangeland management may also include prescribed burning to reduce devastating run-away fires (Hough, 1993).

While the timing of rainfall and rates of vegetation senescence define the predisposing conditions for fires, land uses do influence the exact timing of burning within the window of opportunity provided by these natural conditions. Two recent studies suggest that, in savannah environments, farmers and pastoralists seek to burn most grasses early in the season, as this is the safest and most beneficial way to burn. Mbow, Nielsen and Rasmussen (2000) argue that the main reason for early-season burning in Senegal is to obtain a ‘green flush’ from perennial grasses and to protect landscapes against later and more destructive fires. In Mali, although burning for the green flush is clearly one reason, the earliest burning is carried out on soils that support short annual grasses that have no use for grazing as they do not re-sprout and are not palatable (Laris, 2002). Laris (2002) has shown that the earliest fires in Mali are set when the grasses are just dry enough to burn, and that this is to separate the landscape into burned and unburned patches. After this has been accomplished, herders or hunters gain necessary control over further burning for rangeland management. Only then can they burn particular patches of grassland or savannah at the optimal times for given land uses and ensure that late fires do not sweep through large areas. Late fires are actually damaging to ecosystems, particularly to economically and culturally important trees. Early fires thus have both preventative and protective roles (Laris, 2002).

Study area

The study concerns a small region (198 × 170 km) in the southwestern part of the Central African Republic, between 15 and 17° E and 3 and 5° N (Fig. 1). The region contains a variety of ecotypes: savannah, dense humid and semi-humid forest, and peri-forest. By peri-forest, Boulvert (1986) means the mosaics of dense humid forest and savannahs in the Congo–Guinean domain that turn smoothly into dense semi-humid forest (Table 1). The northern part of the study area covers the domain of

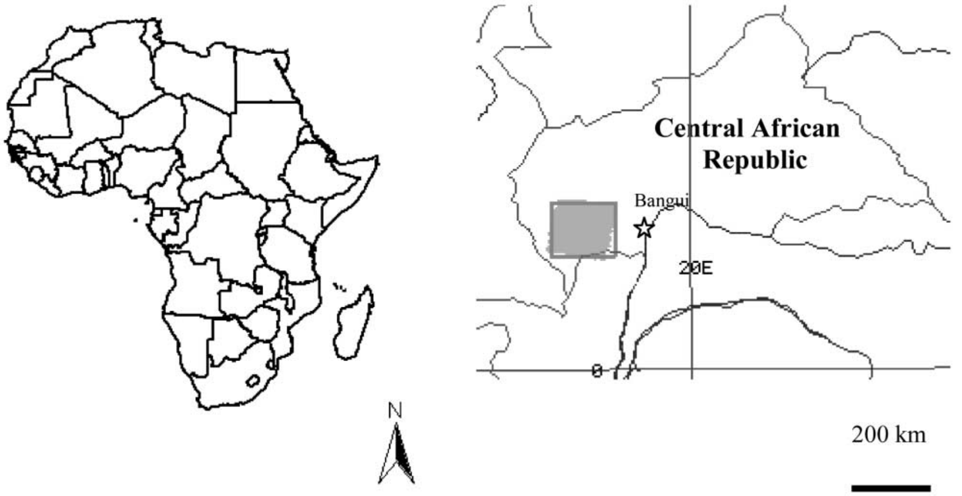

Fig. 1. The study area.

Sudano-Guinean savannahs, with herbaceous savannahs, transition ecotypes and areas of anthropic degradation (Fig. 2). The southern part of the study area is in the Congo–Guinean dense forest domain. Patches of savannah included in the forest are present along some rivers and main roads. In some places, the forest has been cleared and converted into plantations.

The eastern part of the study area is composed, in the north, of dense semi-humid forest with zones of transition and degradation and, in the centre and south, by peri-forest and savannah of anthropic degradation with a patchy landscape. In this region, coffee, cacao, bananas and yam plantations are scattered in the landscape, especially where the cover grades into forest. In the open savannah region, mostly manioc is cultivated. Forest exploitation by logging companies is taking place along the Lobaye river and in the dense humid forest, mostly along roads and rivers.

Fire activity in Central Africa starts with the onset of the dry season in November and, in the study area, finishes with the onset of the rains in late February or early March (Koffi, Gregoire, Mahe, & Lacaux, 1995; Eva & Lambin, 1998a,b). Fires move south during the dry season. Towards the equator, most of the fires occur from December to January, with a peak in late December for the study area. There is a 'drying-out' period at the beginning of the dry season before biomass burning starts (Cooke, Koffi, & Gregoire, 1996). In forests, biomass burning is associated with patches of deforestation or with included savannahs. Fires are also present in the northeastern semi-humid forests and peri-forests.

Data

The dataset used in this study included a map of changes in land cover derived from two Landsat Thematic Mapper (TM) images, a vegetation map of Central Africa

Table 1
Representative taxa for each ecotype of the study area

Ecotype	Representative taxa
Savannahs	*Burkea africana, Lophira lanceolata, Daniellia oliveri, Andropogon gayanus, Hyparrhenia welwitschii, H. familiaris, Pteridium aquilinum, Laudetia arundinacea*
Savannahs included in dense humid forest	*Hymenocardia acida, Annona senegalensis, Bridelia ndellensis*
Dense semi-humid forests	*Anogeissus leiocarpus, Albizia zygia, Daniellia olivieri, Terminalia glaucescens, Cussonia djalonensis, Hannoa undulata*
Peri-forests	*Terminalia glaucescens, Albizia zygia, Pennisetum purpureum, Aframomum latifolium, Hyparrhenia bracteata, Daniellia oliveri, Erythryna sigmoidea*
Dense humid forests	*Triplochiton scleroxylon, Terminalia superba, Mansonia altissima, Holoptelea grandis, Oxystigma oxyphyllum, Petersianthus macrocarpus, Lovoa trichilioides, Autranella congolensis*
Riparian forests	*Uapaca heudelotii, Cathormion altissimum, Mytragina inermis,Diospyros mespiliformis, Kigelia africana*

Source: Boulvert (1986).

and a burnt-area map. All data layers were re-projected in the sinusoidal projection system (Normal Sphere).

Land-cover change data

Changes in land cover were computed on the basis of two Landsat TM images (spatial resolution 30 m) acquired on 26 November 1990 and 16 January 1995 – the closest dates available in the early 1990s. The two images were geometrically co-registered (using a nearest-neighbour resampling) and a mask of clouds and cloud shadows was applied. For both images, the Normalised Difference Vegetation Index (NDVI) was calculated. The land-cover change map was computed from the difference between NDVI values at the two dates. Threshold values of change intensity were defined by visual interpretation to separate the actual changes in land cover from changes due to differences in phenology between the two images. A threshold value of –2.2 standard deviations from the mean difference value was taken for negative changes, corresponding to a decrease in vegetation cover (Fig. 3a). For positive changes, corresponding to an increase in vegetation cover, this threshold was set at +2.0 standard deviations from the mean difference value (Fig. 3b). These land-cover change maps highlight changes in surface attributes that are detectable at 30-m resolution, based on surface reflectance data.

Fire data

The biomass burning data consist of a time series of burnt-area maps produced by Eva and Lambin (1998), who developed a method based on temporal spectral

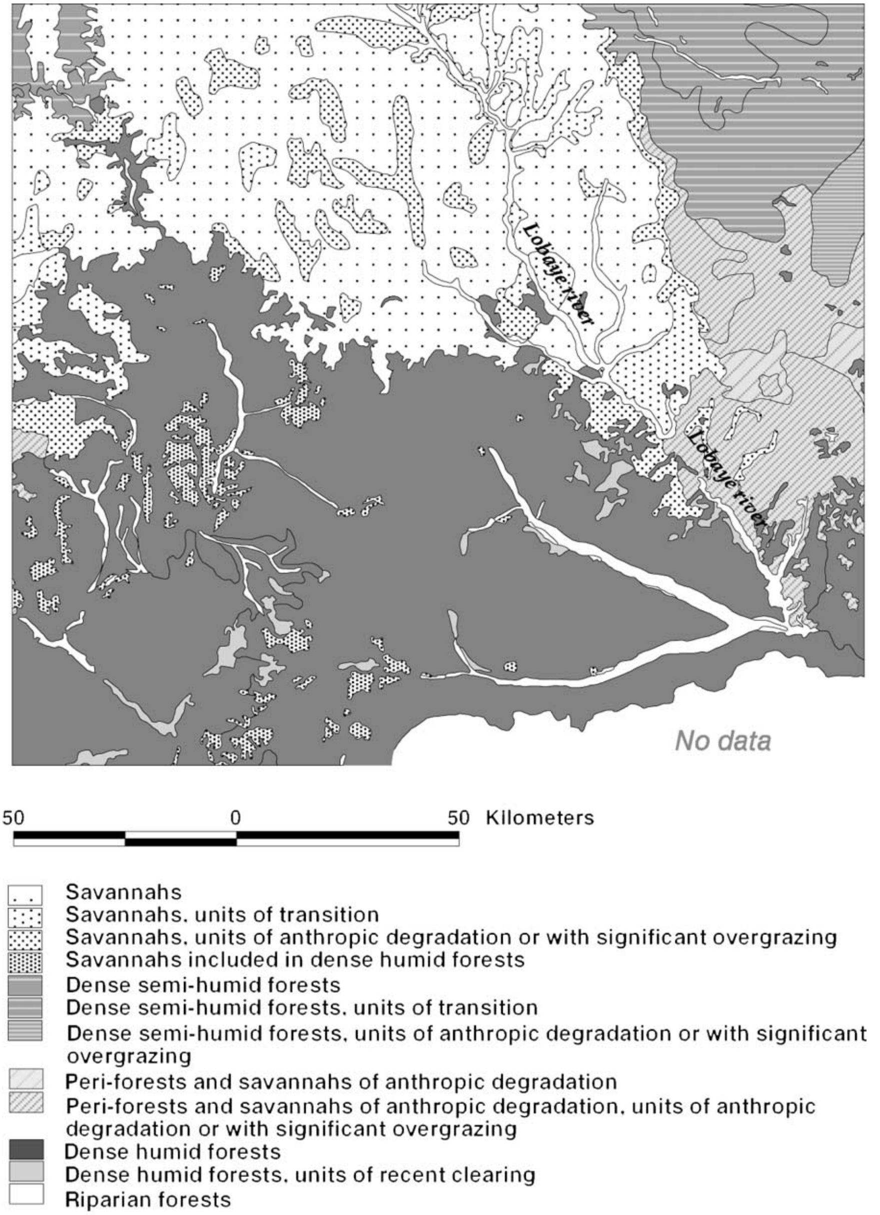

Fig. 2. Phytogeographic map (after Boulvert, 1986).

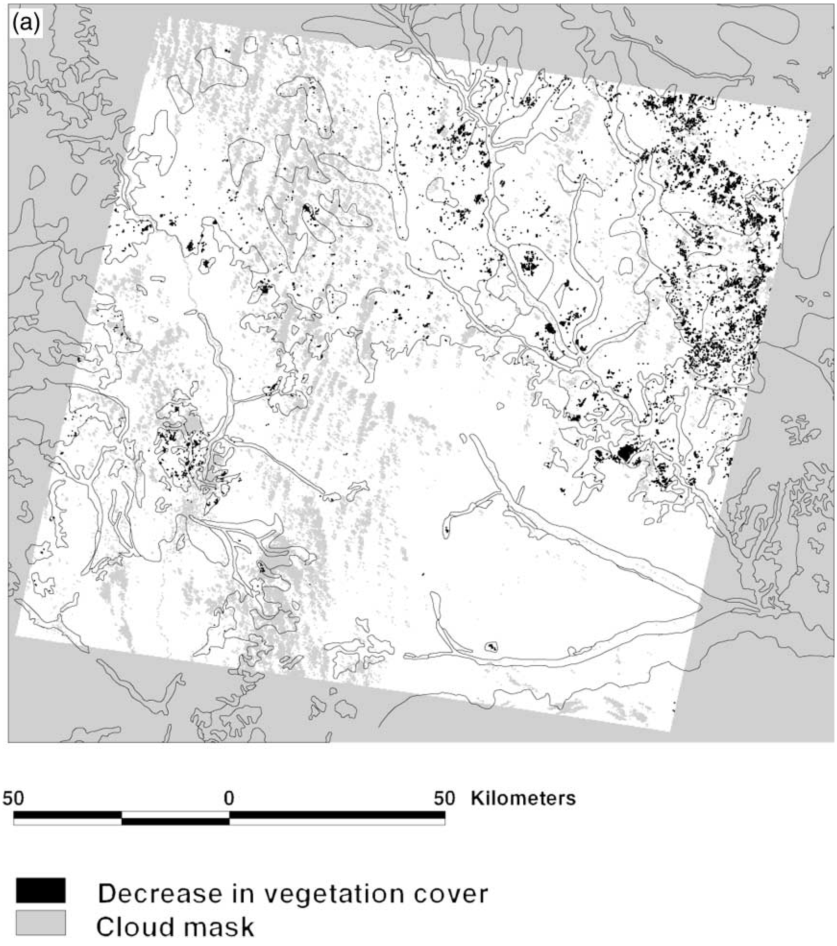

Fig. 3a. Land-cover change: areas of decrease in vegetation cover (positive changes).

profiles for every pixel. This allowed analysis of time series of short-wave infrared and thermal bands of Along Track Scanning Radiometer (ATSR) images. The data have a spatial resolution of 1×1 km and cover the whole of the Central African Republic. The map identifies areas affected by burning in the 1994/5 dry season (15 October 1994 to 10 March 1995) and with a temporal resolution of 10 days. It was validated using airborne video and Landsat TM data. Due to the coarse spatial resolution of the ATSR data, very small and highly fragmented burn patches remain undetected. It is assumed that the 1994/5 burning season is representative of the burning seasons in the early 1990s, as climate conditions for that year were average.

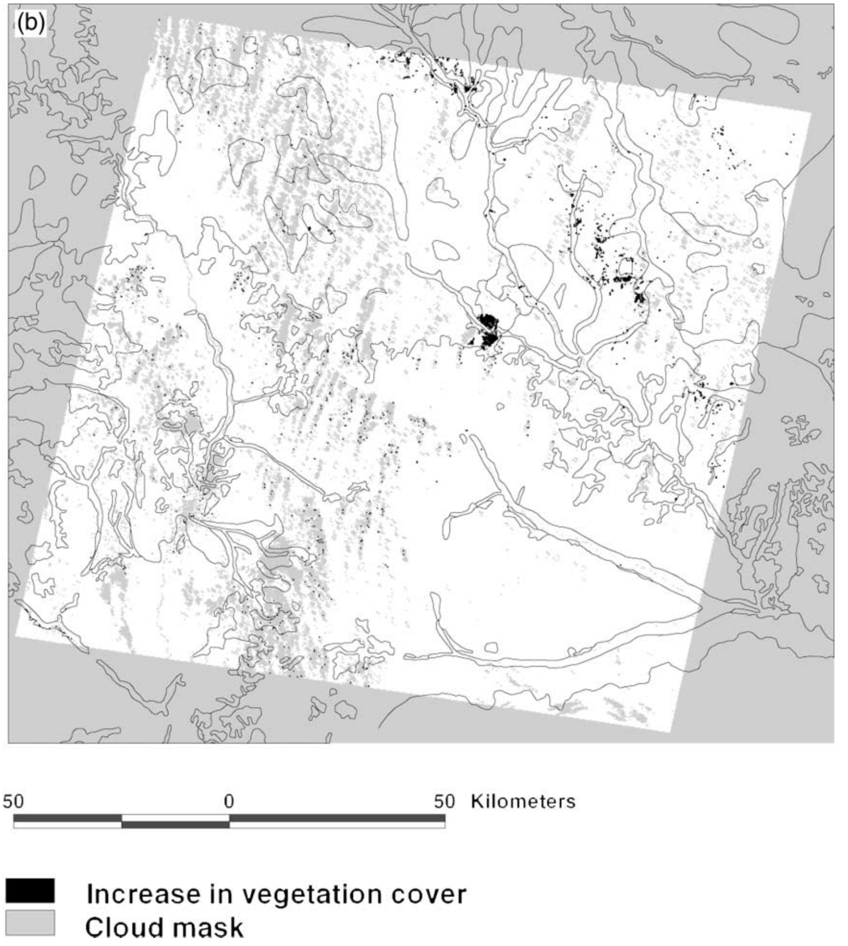

Fig. 3b. Land cover change: areas of increase in vegetation cover (negative changes).

Vegetation data

To characterize the vegetation cover a detailed map of ecotypes at a scale of 1:1 000 000 was used, which had been produced on the basis of extensive field data and Landsat TM images (Boulvert, 1986). No detailed vegetation map of the early 1990s was available. The map was digitized and vegetation classes were attributed to polygons (see Fig. 2). Representative taxa for each ecotype are provided in Table 1.

Methodology

The land-cover change map was overlaid on the burnt area and vegetation maps to analyse the two-way interactions between fires and land cover. First, the spatial association between different ecotypes and the occurrence of fire activity at different time periods was analysed using simple frequency analysis. Second, the impact of fires on land-cover change, for different vegetation types, was analysed with multivariate regression analysis. In the models, land-cover change was defined as the dependent variable and the independent variables represented the occurrence of different burning patterns and vegetation covers. To measure these variables, a grid was created over the study area, with square blocks ($n = 223$) each measuring 11×11 km (Fig. 4). This size minimizes co-registration errors between data layers (of less than a 1-km pixel) and allows measurement of surface percentages with 121 potential values, so that the variable can be considered as a continuous measure. In the multiple regression analyses, all variables were the percentage of the area of a block having a given attribute, calculated by reference to the area of each block that was cloud-free and shadow-free. All blocks with at least 50% of their area cloud

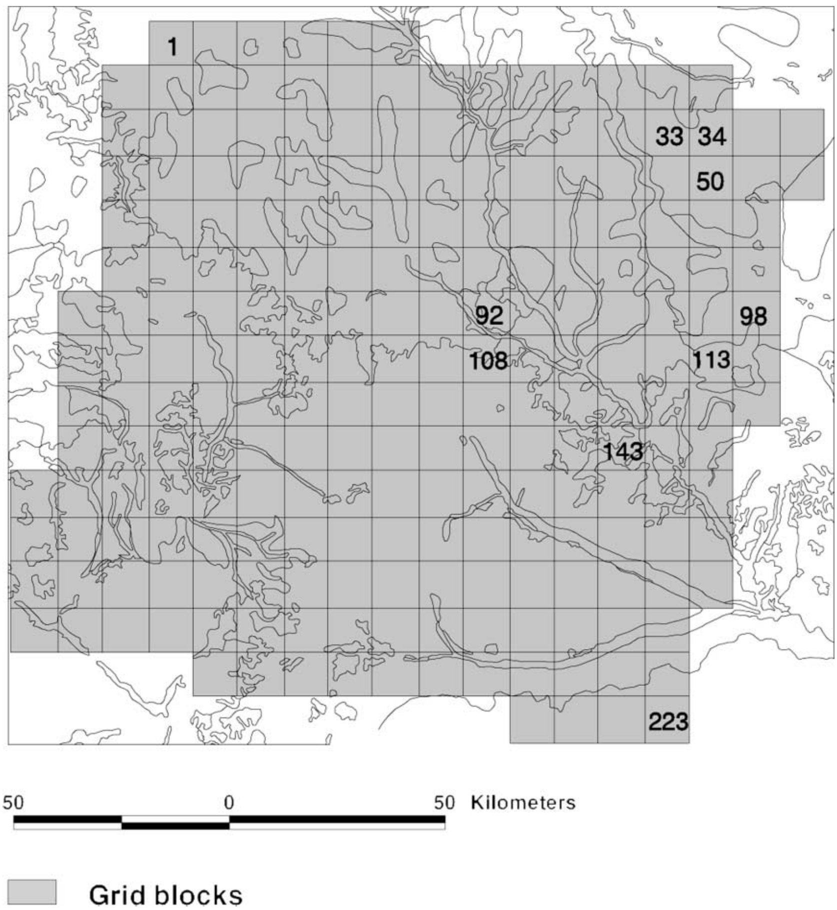

Fig. 4. Grid blocks used for statistical analyses, with block numbers referred to in the text. Only blocks cited in the text are numbered on the figure.

contaminated (which was the case for 41 blocks) were excluded from the analysis. This guarantees that any residual cloud contamination that could be misinterpreted with land-cover change, mostly along cloud edges, does not affect the statistical results.

The negative and positive land-cover changes were treated separately; different models were developed to explain the decrease (see Fig. 3a) and increase (Fig. 3b) in vegetation cover. More than half of the blocks (146) contain burnt patches. The burning season was divided in two periods: the early burning season (15 October 1994 to 31 January 1995; Fig. 5a), and the late burning season (1 February 1995 to 10 March 1995; Fig. 5b). These dates represent the average burning periods for the study area, even though there are slight lags in the timing of rainfall and vegetation senescence along the ecosystem gradients of the region. For some blocks, burnt areas

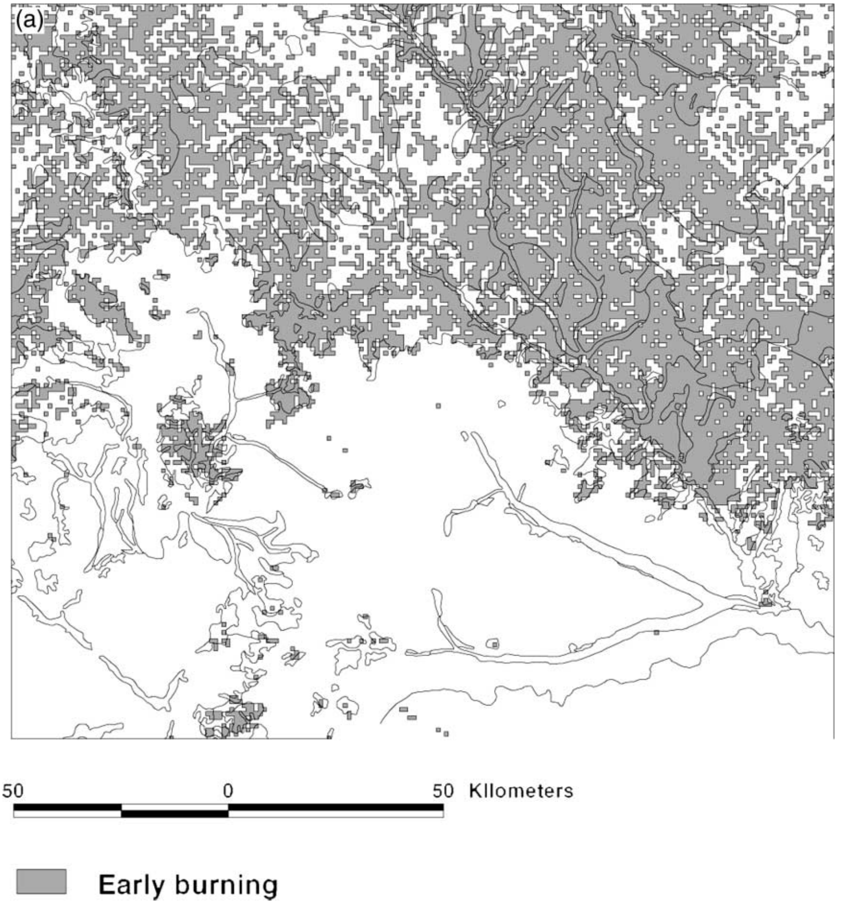

Fig. 5. Burnt-area map (after Eva & Lambin, 1998): (a) areas affected by early burning (15 October 1994 to 31 January 1995); (b) areas affected by late burning (1 February 1995 to 10 March 1995). Note the absence of burnt areas in the dense humid forest zone.

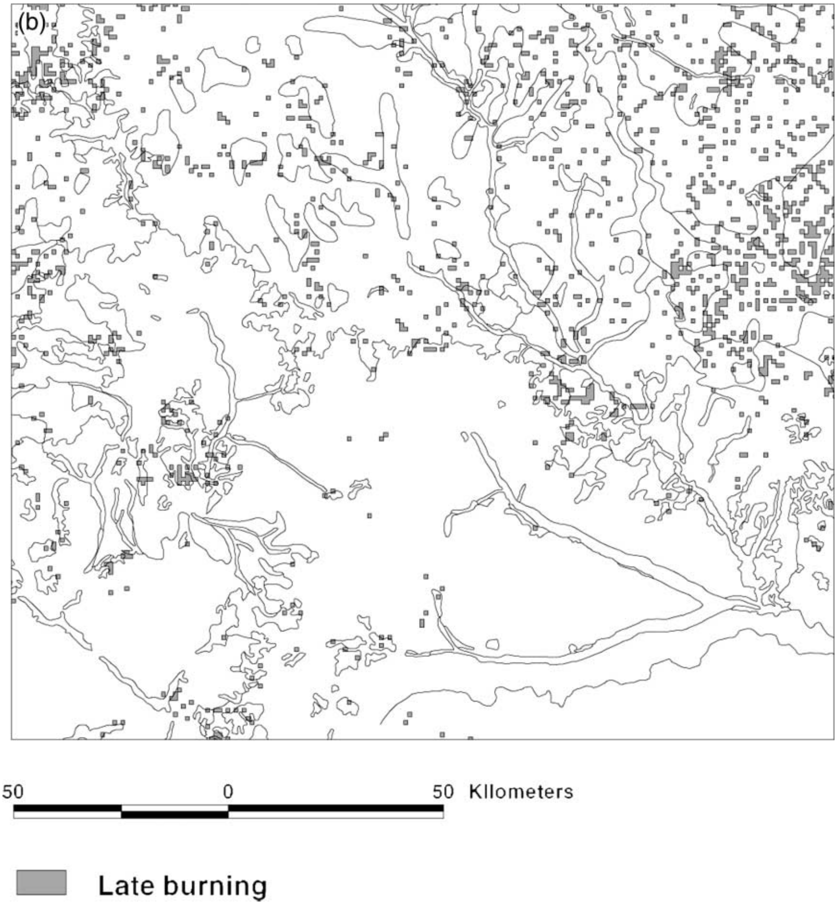

Fig. 5. *Continued*

were detected twice in a season, suggesting that different parts of a block did burn at different periods of the year. For each block and each period, the spatial pattern of burning was characterized in terms of continuous or fragmented burnt patches. This was based on the proportion of the block covered by burning, the number of patches in a block and their total perimeter. In summary, the variables related to burning were defined as the percentage of the area of a block covered by pixels burnt: (1) early in the dry season, with a continuous burnt area, (2) early in the dry season, with a fragmented burnt area and (3) late in the dry season, with a fragmented burnt area. All fires taking place late in the season were fragmented and therefore the fourth possible category (continuous burnt areas late in the burning season) was not represented.

The vegetation classes of the ecotype map were merged according to Boulvert's classification: the savannah sector (35.8% of the study area), the dense forest sector (which was further subdivided into dense semi-humid and dense humid forests, respectively 9.3 and 43.3% of the study area), and the sector with peri-forests and savannahs of anthropic degradation (8.3% of the study area). Gallery forests form the remaining 3.3% of the study area. They are frequently affected by inundations and are thus too moist for burning. The percentages of the area of a block covered by each broad ecotype category were used as independent variables in the multiple regression analysis.

The model explaining the decrease in vegetation cover was improved by dividing the study area into two regions and treating each separately: one region included blocks with more than 10% of their area covered by peri-forests ($n = 21$) and the other included blocks mainly covered by forests and savannahs, with less than 10% of peri-forests ($n = 161$). This separation was justified, given the different behaviour of peri-forests with respect to fires compared to the other ecotypes, as shown in a preliminary statistical analysis.

Results

Influence of vegetation cover on the spatial distribution of fires

Histograms of fire occurrence for the different ecotypes (Figs 6a and 6b), together with the ecotype and burnt-area maps, represent the fire distribution throughout the landscape of the study area.

Savannah

Overall, 54.1% of savannahs in the study area were affected by early fires, while the percentage of late burning was much lower (4.4%). If savannah fires take place early in the dry season, then the more destructive late fires are limited (Cooke et al., 1996). Savannahs, savannahs of transition and savannahs of anthropic degradation show similar fire activity in the two periods of the dry season: mostly early burning, and very few and small late fires. Among the three classes, savannahs of transition are most affected by burning. This ecotype is mostly located along roads and around villages, suggesting a strong association between these fires and land use activities. For the savannahs included in the dense humid forest, which are also used for human activities, the percentage of early burning is much higher than in dense humid forests but lower than in open savannahs.

Dense semi-humid forest

A high density of burnt scars was detected in the dense semi-humid forests, which are located at the edge of the large forested areas extending toward the northeast. There is a decreasing density of early burnt scars from the borders to the inner part of dense semi-humid forests. Fires invade these forests from surrounding peri-forests and savannahs. Late during the dry season, a relatively high percentage of burning (10.7%) affects this ecosystem in the form of small, scattered burnt areas.

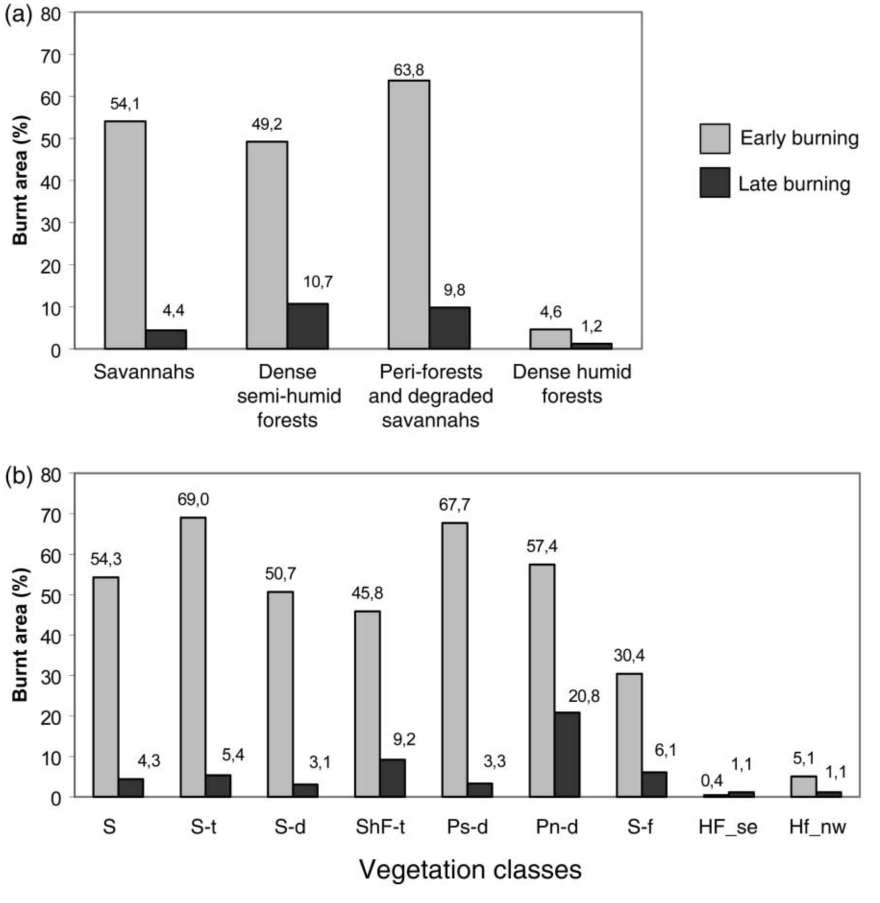

Fig. 6. Frequency of fire occurrence for the different ecotypes:(a) for the broad vegetation classes according to Boulvert's classification; (b) for selected ecotypes from Boulvert's detailed classification. S=Savannahs; S-t=Savannahs, units of transition; S-d=Savannahs, units of anthropic degradation or with significant overgrazing; ShF-t=Dense semi-humid forests, units of transition; Ps-d=Peri-forests and savannahs of anthropic degradation, units of anthropic degradation; or with significant overgrazing, southern sector; Pn-d=Peri-forests and savannahs of anthropic degradation, units of anthropic degradation; or with significant overgrazing, northern sector; S-f=Savannahs included in dense humid forests; HF-se=Dense humid forests, south-eastern sector; HF-nw=Dense humid forests, north-western sector.

Peri-forest and savannahs of anthropic degradation

Units of anthropic degradation or serious overgrazing are the main components of this sector, which is the one most affected by burning. Here the different ecotypes form a complex mosaic and the spatial patterns of burning cuts across all ecotypes. Plantations are present in the southern part of this sector. In these units, land use controls the burning regime more strictly. Human intervention aims at avoiding fires late in the season, as shown by the low occurrence of late fires (around 3% of the area) (see Fig. 6b). By contrast, in the northern parts of the sector, where no human settlements are found, fires occur both early and late in the dry season (around 21% of the area for the later). In this region, late fires are widespread and form burnt patches of several square kilometres. This suggests that, where human control over fires is weaker, they are more evenly distributed throughout the entire burning season. Late burning is likely to be associated with runaway fires that are the outcome of less control on fire regime.

Dense humid forests

In dense humid forests, fires are different in frequency and spatial pattern compared with the other ecotypes. The dense humid forest clearly bounds the burning front and fires affect only a small fraction of this ecosystem (see Fig. 5). The detected fire events take place at the border of included savannahs and forest clearings, and are associated with logging or land clearing activities.

Impact of fires on land-cover change for different vegetation types

Statistical considerations

For all models presented below, the distribution of residuals showed a good agreement with the Gaussian distribution. Also, for all models, the possible influence of spatial autocorrelation was tested by computing conditional spatial autoregressive models (Cressie, 1993). In all cases, spatial dependence was negligible and the independent variables captured most of the variation. As the variables describing the presence or absence of savannahs and forests were complementary (and thus highly correlated), they were introduced in separate models.

Decrease in vegetation cover (negative changes)

Two models were developed to explain the decrease in vegetation cover for observations from blocks mainly covered by savannah and forest ecosystems (i.e. with less than 10% of peri-forests and degraded savannahs), with one model including ‘presence of savannahs’ as an independent variable and one including ‘presence of forests’. In both cases, the adjusted multiple R^2 was high and significant (.529 and .526 with $\alpha < .001$ in both cases) (Table 2). All burning variables (late and early, fragmented and continuous) were significant in both models, with positive signs for all coefficients. The vegetation cover variables (i.e. presence or absence of either savannahs or forests) were also significant, with coefficients having comparable absolute values but opposite signs. This result reveals the fundamental difference in the impact of fires on savannahs and forests. The positive sign of the coefficient for forests, together with the positive sign of the coefficients for the variables representing burning, indicate that the occurrence of land-cover change is associated with fires occurring in forests. By contrast, the negative coefficient for open savannahs indicates that no (or negligible) land-cover changes occurred in areas of savannah affected by fire. The savannahs regenerated rapidly after burning, in contrast with dense forests, which appeared to be vulnerable to fires.

The two-dimensional plots between land-cover change and the independent variables (Fig. 7) reveal that all blocks with the highest values of land-cover change

Table 2
Regression models for the dependent variable 'decrease in vegetation cover' for blocks with <10% of their area as peri-forest

Independent variable	Coefficient	Standard error	*t*	*p* (two-tail)
(a) Model including 'savannah' as one of the independent variables[a]				
Constant	.001	.001	.657	.512
Early continuous burning	.065	.008	8.352	.000
Early fragmented burning	.096	.015	6.357	.000
Late fragmented burning	.169	.041	4.160	.000
Savannahs	–.031	.005	–5.721	.000
(b) Model including 'dense forest' as one of the independent variables[b]				
Constant	–.027	.005	–5.390	.000
Early continuous burning	.064	.008	8.226	.000
Early fragmented burning	.091	.015	6.210	.000
Late fragmented burning	.170	.041	4.165	.000
Forests	.030	.005	5.584	.000

[a] $n = 161$; adjusted $R^2 = .529$ ($\alpha < .001$); standard error estimate = .014.
[b] $n = 161$; adjusted $R^2 = .526$ ($\alpha < .001$); standard error estimate = .014.

(more than 10%) have been affected by fire activity both early (either continuous or fragmented) and late in the dry season. For example, blocks 33, 34 and 50 (see Fig. 4) are dominated by dense semi-humid forest bordering degraded areas of savannah and peri-forest (see Fig. 2). A significant decrease in vegetation cover was observed in these blocks (see Fig. 3a), probably due to an expansion of pastoral activities during the 1990–5 period, at the edge of the dense humid forest. This expansion was associated with repeated burning. Moreover, the ATSR maps revealed large fires initiated in the savannah or peri-forest that have expanded into the forest and have led to forest-cover changes. As another example, block 143 (see Fig. 4) presents more than 10% of negative land-cover change in a complex arrangement of covers where all classes co-occur (see Figs 2 and 3a). It is an important zone of transition located at the edge of Lobaye river and including several villages in forest clearings. Coffee and palm plantations are identified in Boulvert's map in this area. The detected land-cover changes associated with fire activity at the edge of forested areas suggest that further land conversion for plantations has occurred since 1990, using fire as a tool.

The model explaining the decrease in vegetation cover for blocks with more than 10% of peri-forests and degraded savannahs reveals that a significant and positive relationship is found between the decrease in vegetation cover and late fires with fragmented burnt areas (adjusted $R^2 = .526$, $\alpha < .001$) (Table 3). Late fire activity thus has an important impact on peri-forests. Savannahs, forests, plantations and pastures are mixed with peri-forests in this area. Given the complex spatial arrange-

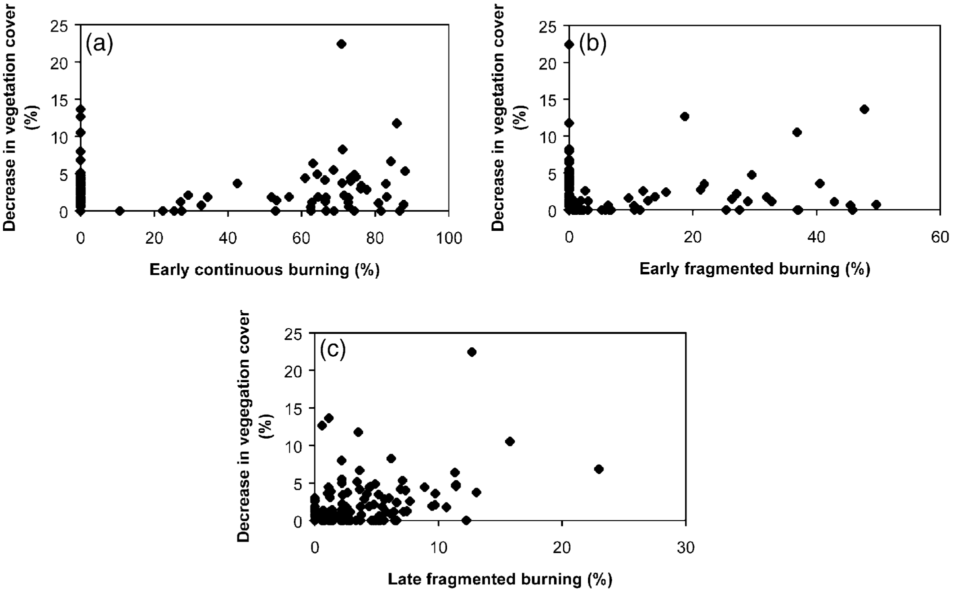

Fig. 7. Two-dimensional scatter-plots for blocks covered by <10% of peri-forests, with decrease in vegetation cover *versus*: (a) early fires with continuous burnt areas; (b) early fires with fragmented burnt areas; (c) late fires with fragmented burnt areas.

Table 3
Regression model for the dependent variable 'decrease in vegetation cover' for blocks with >10% of their area as peri-forest[a]

Independent variable	Coefficient	Standard error	*t*	*p* (two-tail)
Constant	.039	.014	2.804	.012
Late fragmented burning	.529	.113	4.700	.000

[a] $n = 21$; adjusted $R^2 = .526$ ($\alpha < .001$); standard error estimate=.041.

ment of vegetation types, different vegetation covers in an area reach senescence at different times in the dry season. Interactions between vegetation cover and burning early in the season are therefore complex and spatially heterogeneous. By contrast, late in the season, the entire vegetation cover is senescent and has a high flammability, which leads to a significant relationship between the decrease in vegetation cover and late-season burning. The two-dimensional plots reveal the presence of negative land-cover changes in all blocks with more than 10% of peri-forests (Fig. 8a). Most changes are associated with late season burning (Fig. 8b). The blocks with the largest areas of land-cover change surround the town of Boda (blocks 98 and 113; see Fig. 4) in a zone described by Boulvert in 1985 as undisturbed peri-forest.

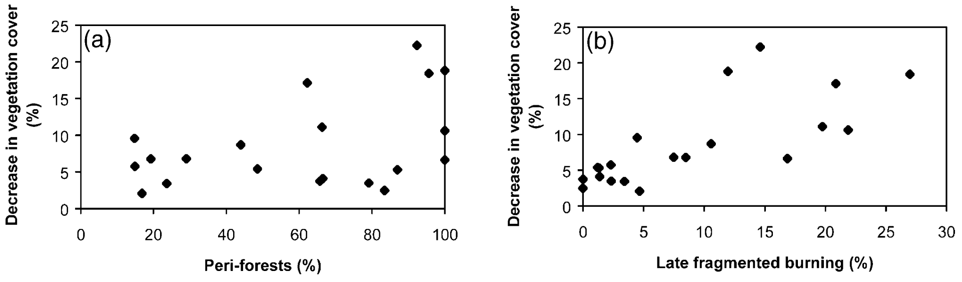

Fig. 8. Two-dimensional scatterplots for blocks covered by >10% of peri-forests, with decrease in vegetation cover *versus*: (a) peri-forests; (b) late fires with fragmented burnt areas.

Recent land-cover changes associated with fires are likely to be related to farming activities around the town.

Increase in vegetation cover (positive changes)

The multivariate model of the increase in vegetation cover as a function of burning patterns and ecotypes did not explain in a statistically significant way the observed positive changes in vegetation cover. The increase in vegetation cover never affects more than 10% of the surface of a block (Fig. 9), which is lower than for the decrease in vegetation cover. Blocks affected by vegetation increase are characterized by a high spatial heterogeneity in vegetation cover and burning patterns. Vegetation increase mostly takes place in savannahs affected by early continuous burning, with a quasi-absence of late burning (see Figs 3b and 9). This suggests that early fires do not prevent a gradual increase in woody vegetation. By contrast, even a low occurrence of late burning seems to be negatively associated with vegetation increase (Fig. 9b). The increase in vegetation cover mostly takes place along the Lobaye river and its tributaries (blocks 92 and 108; see Fig. 4), where protracted inundations frequently occur and riparian forests dominate the river's edges. After early burning,

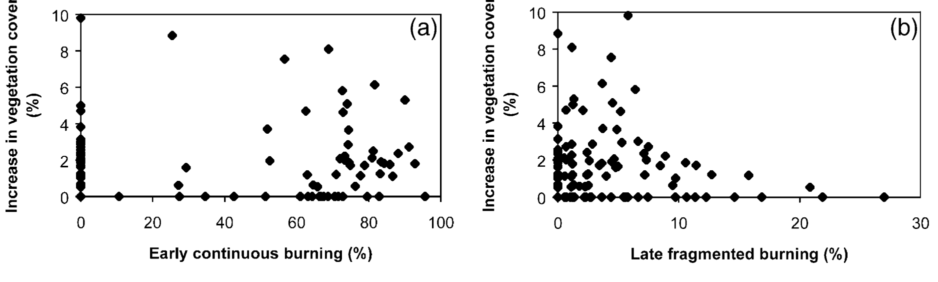

Fig. 9. Two-dimensional scatterplots of increase in vegetation cover *versus*: (a) early fires with continuous burnt areas; (b) late fires with fragmented burnt areas.

the vegetation of savannahs is likely to regenerate rapidly in this ecosystem, which benefits from long periods with high soil moisture (Fig. 10).

Conclusion

Using multiple regression models to explain changes in vegetation cover as a function of burning patterns and vegetation types, this study has advanced previous work by Ehrlich et al. (1997) and Eva and Lambin (2000) on the impact of fires on land-cover change in two ways. First, the scale of analysis is finer. Second, the characterization of biomass burning events was greatly refined as it was based on burnt areas rather than active fires. This allowed improved analysis of spatial associations between landscape attributes and burning events. In dense forests, burning is strongly associated with land-cover changes. In savannahs, the occurrence of (mostly) early fires and (fewer) late fires is not associated with land-cover change. These results are consistent with the findings of others and with ecological understanding of the role of fire as a disturbance (e.g. Goldammer, 1990, 1999; Eva & Lambin, 2000). Fires associated with continuous and fragmented burnt patches have the same impact on vegetation cover. Thus, our data do not support the hypothesis that fragmented burnt patches indicate incomplete combustion and are therefore associated with a lower impact on vegetation than continuous burnt patches.

This study has also revealed that dense semi-humid forests in the study area were affected by a remarkably high level of burning, both early and late in the dry season. This was associated with particular land uses and led to forest-cover changes. In general, forest ecosystems remain protected from fire (Boulvert, 1986). However, in the study area, these forests border degraded savannahs and peri-forests, from which human land uses are expanding. Peri-forests are also affected by land-cover change but, due to the complex landscape structure, only late burning was associated with land-cover changes.

The results confirm recent findings by Mbow et al. (2000) and Laris (2002) concerning human control on the timing of burning in savannahs. Around human settlements, land use is associated with early burning, which leads to very limited late burning. Early fires actually fragment the landscape, preventing the spatial diffusion of later damaging fires (Laris, 2002). Where no human settlements are present, the proportion of early fires decreases and late fires become more prevalent. This highlights the strong link between land use and burning regime. Finally, this study measured an increase in vegetation cover in a few areas affected by very early burning (end of November, beginning of December). This suggests that, under certain conditions (along rivers and near riparian forests, where soil moisture is still high late in the dry season), fires do not prevent a regrowth of vegetation.

The diversity of human activities in the study area (small-scale farming, pastoralism, plantations, hunting and logging) makes the analysis of the proximate causes of fires difficult. A complementary analysis of spatially disaggregated socioeconomic and land-use data would allow improvement of the interpretation of the role of land use as a controlling factor of burning regimes. However, this would require signifi-

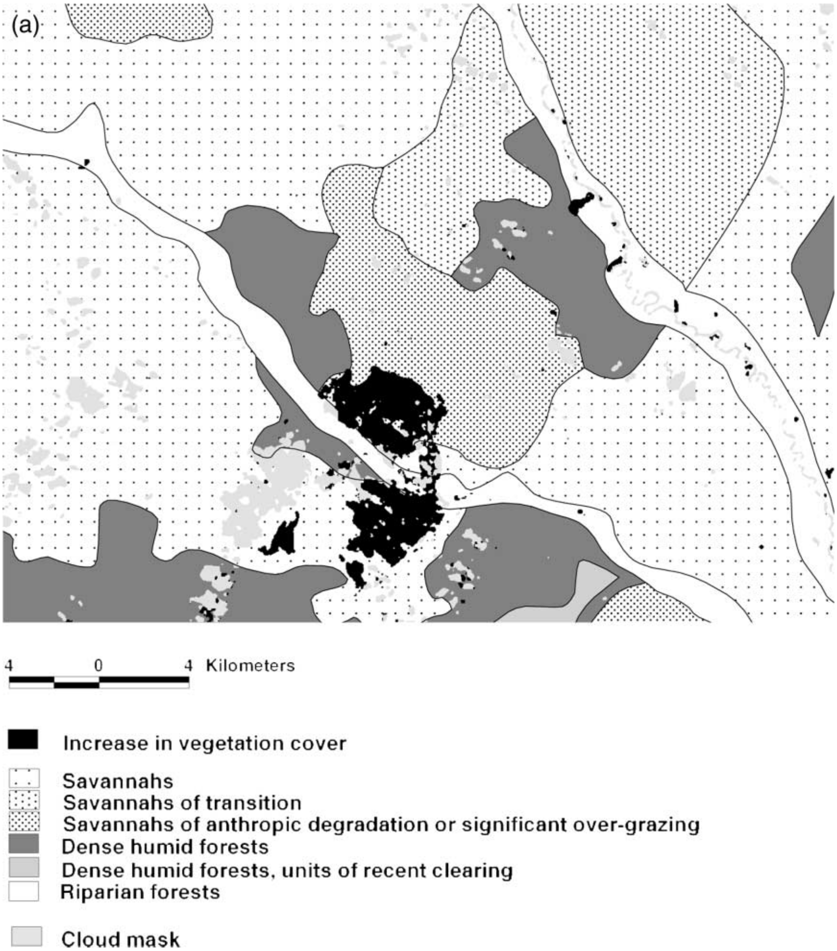

Fig. 10. Areas of vegetation increase (blocks 92 and 108) along Topia river, in areas of degraded and undegraded savannahs in a dense humid forest sector. The areas of vegetation increase undergo burning early but not late in the dry season. (a) Areas of increase in vegetation cover overlaid on Boulvert's ecotype map. (b) Areas of increase in vegetation cover, and burnt areas corresponding to early fires.

cant data collection on land-use practices, to understand how land managers make decisions on burning. Other limitations of the present study include the nature of land-cover change detected by remote sensing – changes in vegetation cover but not subtle changes in floristic composition or soil nutrient content – and the timing of the land-cover change data (November 1990 to January 1995) compared to the burnt area data (1994/5 burning season).

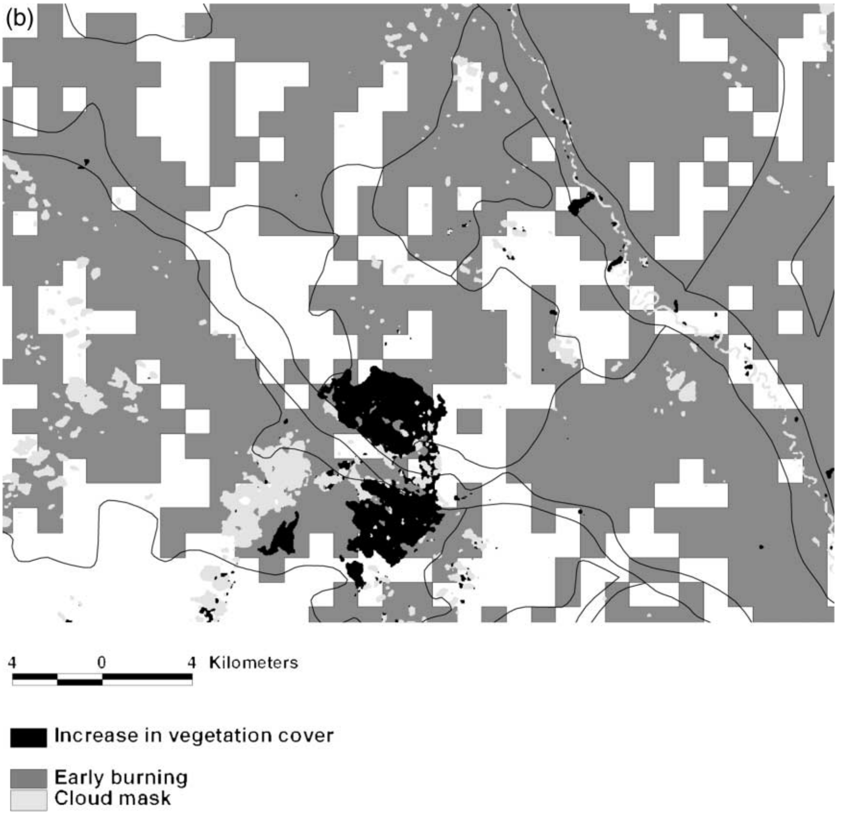

Fig. 10. *Continued*

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