

# Sharp transitions in microclimatic conditions between savanna and forest in New Caledonia: Insights into the vulnerability of forest edges to fire

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**Abstract** Fires are one of the main causes of forest loss in the tropics. Understanding the dynamic edge effects is critical for managing fires and protecting forests. We measured and analysed trends in microclimatic conditions (air temperature, relative humidity and vapour pressure deficit) over 7 months along three transects extending from core savanna areas to core forest areas. We tested two hypotheses: (i) that the forest edge is subject to microclimatic edge effects, and (ii) that the depth of these edge effects increases during dry periods. Sharp changes in each microclimatic variable were consistently observed between savanna and forest throughout the study period. Microclimatic transitions took place within 5 m outside the forest boundary. Drought levels increased homogeneously throughout the forest and were not disproportionately severe in the vicinity of the forest edge. We suggest that these results were related to the fact that the studied period was abnormally humid due to a *La Niña* episode, and that under such conditions the vulnerability of the forest edge to savanna fires is relatively low. Relatively wet conditions in the savanna close to the forest edge may promote forest expansion by limiting fire spread. Prescribed fires during humid years could reduce fuel loads in savanna without affecting the forest edge, which would prevent fires during the dry years associated with *El Niño* episodes from having severe impacts.

**Key words:** boundary, ecotone, edge effect, forest understorey, vapour pressure deficit.

## INTRODUCTION

Human-induced fires have become an increasingly serious threat to tropical forests over the last few decades (CBD 2001). Indeed, one of the main causes of forest loss in the tropics is from fires penetrating forest edges from adjacent open vegetation communities (Goldammer 1999; Nepstad *et al.* 1999; Cochrane 2003). Forest fragments surrounded by a matrix of lower biomass and structural complexity such as pastures or savannas are affected by multiple edge effects (Murcia 1995; Fonsca & Joner 2007). Fire behaviour in such landscapes is sensitive to changes in both microclimate and vegetation cover (Whelan 1995; Stott 2000), both of which strongly influence the vulnerability of forest edges to subsequent fires in the surrounding matrix (e.g. Cochrane & Laurance 2002; Cochrane 2003). Measuring and understanding the

dynamics of such edge effects is critical for managing fires and protecting forests.

The flammability of forests in the tropics is relatively low when compared with adjacent open vegetation communities (Hoffmann *et al.* 2012; Little *et al.* 2012). As a result, fires that start in forests tend to propagate slowly with low intensity and do not penetrate deeply into the forest understorey (Cochrane *et al.* 1999; Stott 2000). Nevertheless, because forest trees are not adapted to fire (Hoffmann *et al.* 2003; Ibanez *et al.* 2013), these fires can cause significant mortality and changes in the vegetation structure (e.g. Barlow & Peres 2008). Like logging, fires therefore cause changes in the forest's structure, fuel composition and microclimatic conditions, which facilitate the propagation of subsequent fires and thus increase the vulnerability of forest stands to future fires (Cochrane *et al.* 1999; Siegert *et al.* 2001; Barlow & Peres 2008). However, the flammability of the forest can be reduced in the immediate aftermath of a fire due to removal of flammable fuels from prior combustion (Balch *et al.* 2008).

In the New Caledonian (NC) biodiversity hotspot (Myers 2003; Mittermeier *et al.* 2004), more than half of the original vegetation (mainly forest) has already been destroyed and replaced by anthropogenic formations over the last few centuries, primarily

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because of anthropogenic fires, mining and logging (Jaffré *et al.* 1998). On volcano-sedimentary substrates, forests have primarily been replaced by savannas. Consequently, at intermediate elevations, the New Caledonian landscape consists of a mosaic of savanna and forest patches (e.g. Ibanez *et al.* 2012). Anthropogenic fires are regarded as one of the major threats to the New Caledonian forest and terrestrial biodiversity (Jaffré *et al.* 1998; Pascal *et al.* 2008). It has long been suggested that anthropogenic fires ignited in open areas such as savanna erode the forest edge (Jaffré *et al.* 1997). This hypothesis was recently reinforced by remote sensing analysis of fires (Curt *et al.* submitted, 2012) and vegetation (Ibanez *et al.* 2012), and by fire modelling analysis (Hély *et al.* unpubl. data, 2011). Over the last decade, savannas have been the most frequently burnt vegetation type in NC with 65% of these savanna fires reaching forest edges (Curt *et al.* submitted, 2012). The behaviour of fires at the boundary between savanna and forest is dependent on fuel composition and microclimatic conditions between vegetation types (see Hennenberg *et al.* 2006; Hoffmann *et al.* 2011). However, little is known about the conditions that determine whether savanna fires will penetrate forest edges and continue to burn in the forest.

In this study we investigated the variation in microclimatic conditions along transects from savanna to forest cores. The air temperature, relative humidity and vapour pressure deficit along these transects were monitored continuously over a 7-month period and the resulting data were analysed to test the hypotheses that: (i) the forest edge is subject to microclimatic edge effects and (ii) the depth of these edge effects increases during dry periods. Finally, we discuss the extent to which microclimatic edge effects allow savanna fires to erode forest edges during dry periods.

## METHODS

### Study site

The New Caledonian archipelago is located in the south Pacific (between 20–23°S and 164–167°E) just above the Tropic of Capricorn, about 1500 km east of Australia and 2000 km north of New Zealand. It has a tropical oceanic climate with both cool (June to September) and hot (October to May) seasons, both of which overlap with a characteristic dry season from August to November (<http://www.meteo.nc>). The dry season is characterized by low rainfall, rising temperatures and easterly trade winds, and coincides with the bushfire season. The variability of the New Caledonian climate is primarily governed by the *El Niño* Southern Oscillation phenomenon (Ropelewski & Halpert 1987); that is, during *El Niño* phases the rainfall decreases (to less than 50% of its usual value), whereas during *La Niña* phases a roughly opposite trend is observed (Delcroix & Lenormand 1997).

The study site was located on the western side of the *Aoupinié* mountain (21°11'S and 165°15'E) at about 500 m. a.s.l. The typical annual precipitation at the site ranges from about 1500 to 3000 mm and the mean annual temperature is about 20°C.

### Monitoring microclimatic conditions

Microclimatic variables, including air temperature (T, °C) and relative humidity (RH, %), were monitored using data loggers (HOBO Pro-V2 U23, Onset, Cape Cod, MA) located on three transects 100 m in length (20 m in savanna and 80 m in forest) running perpendicularly to the forest edge and separated from one another by 50 m (Fig. 1). We positioned 12 data loggers along each transect – three in savanna sites, one on the savanna–forest boundary and eight in forest sites. The data logger sites were located in relatively close proximity to one another around the savanna–forest boundary in order to better characterize the transition (i.e. the form of the gradient) in microclimatic conditions in this region. All data loggers were placed on 1-m high poles and shielded from radiation and rainfall to avoid bias. The T and RH were measured every 20 min over a 212-day period running from 4 April 2010 (Julian day 94) to 1 November 2010 (Julian day 305). This period overlapped with the expected dry season, which started in August (Julian day 212).

### Data analysis

We computed hourly T (°C) and RH (%) values as the mean of the maximum and minimum values measured during each hour. These hourly means were used to compute the vapour pressure deficit (VPD, in units of kPa), which is the difference between the amount of moisture in the air ( $VP_{\text{air}}$ ) and the amount of moisture the air can hold when saturated ( $VP_{\text{sat}}$ , see Arya 2001),

$$VP_{\text{sat}} = f(T) \quad (1)$$

$$VP_{\text{air}} = VP_{\text{sat}} \times RH/100, \quad (2)$$

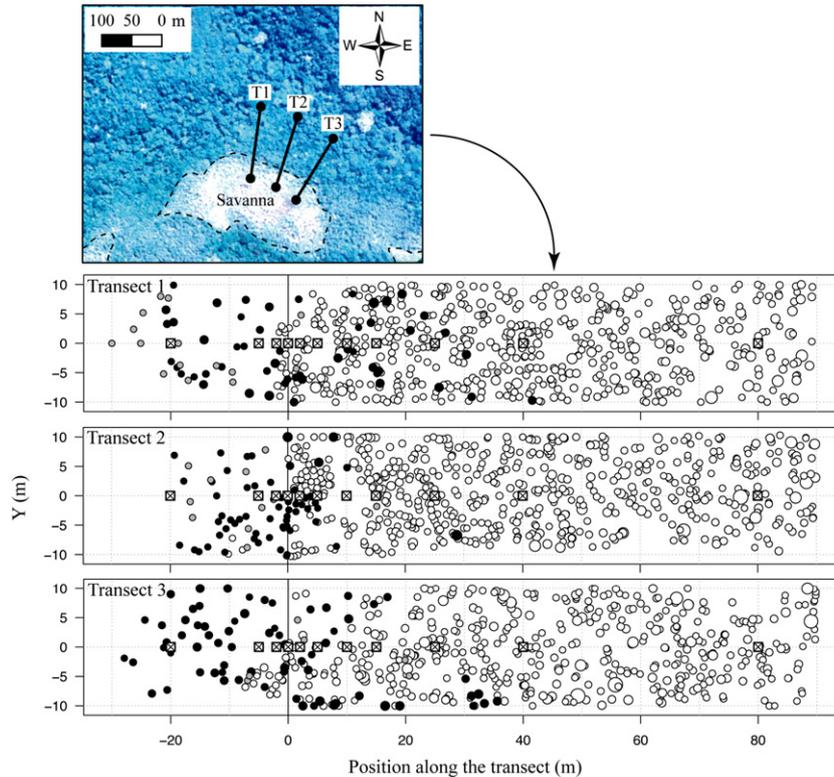
$$VPD = VP_{\text{sat}} - VP_{\text{air}}. \quad (3)$$

The VPD is a particularly interesting variable when analysing and assessing the vulnerability of forest edges to fire because it is a good proxy for the moisture content of the litter, which has a profound impact on fire behaviour (see Ray *et al.* 2005, 2010).

We used the border and ecotone detection analyses (BEDA) presented by Hennenberg *et al.* (2008) to detect variation in microclimate between savanna and forest. BEDA is based on a non-linear sigmoidal function,

$$f(x) = a + (c - a) / (1 + \exp^{-(x-b)/d}), \quad (4)$$

where  $f(x)$  is the value of the studied statistic (T, RH or VPD), calculated as a function of the position along the transect ( $x$ ),  $a$  and  $c$  represent the upper and lower asymptotes (estimated mean conditions in the two adjacent



**Fig. 1.** Positions of the microclimatic stations (squares with crosses) along the three studied transects (in the savanna at  $-20$ ,  $-5$  and  $-2$  m, on the boundary at  $0$  m and in the forest at  $2$ ,  $5$ ,  $10$ ,  $15$ ,  $25$ ,  $40$ ,  $60$  and  $80$  m). Black and grey circles represent living and dead savanna trees (*Melaleuca quinquenervia*), respectively; white circles denote forest trees. The circles' diameters are proportional to the trees' diameter at breast height (DBH) values. The black vertical line indicates the location of the forest edge as determined by field observations.

habitats),  $b$  is the distance to the inflection point, which is an objectively estimated location for the boundary between the two adjacent habitats, and  $d$  characterizes the steepness of the change in the studied statistic. The limits of the ecotone (E1 and E2), which are equivalent to the depth of edge influences (DEIs) towards the two habitat cores, are given by,

$$E1 = b + 2d, \quad (5)$$

and

$$E2 = b - 2d. \quad (6)$$

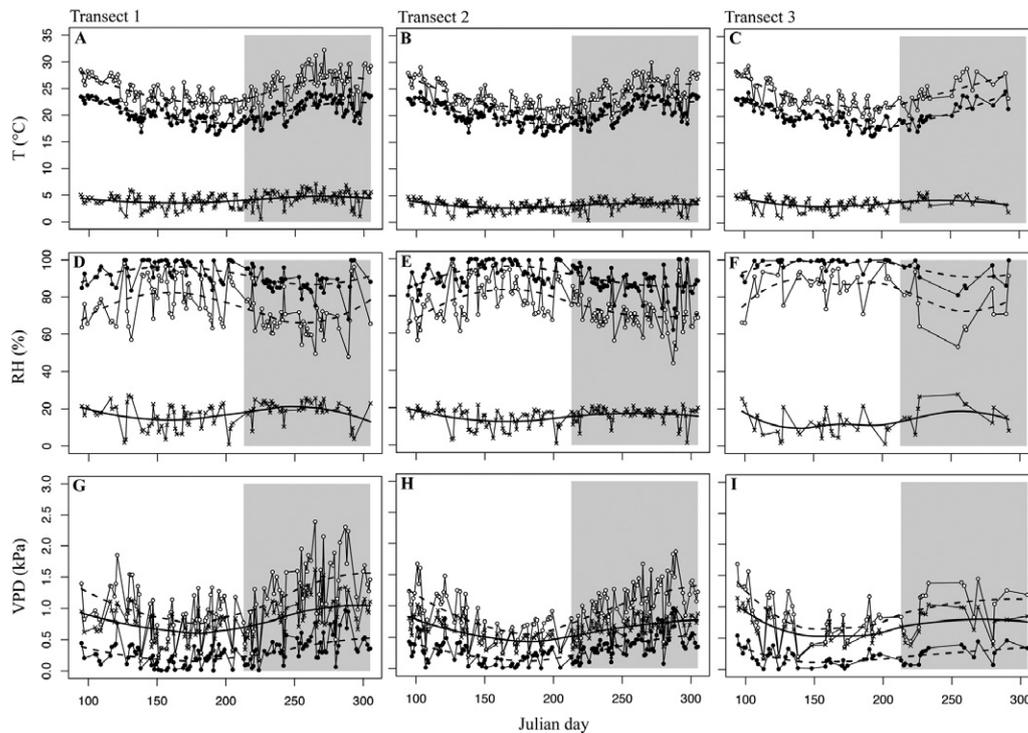
We performed BEDA based on diurnal mean values (from 8.00 to 16.00 hours) to analyse and compare the temporal variations in: (i) the mean conditions in savanna and forest cores and (ii) the DEIs and the positions of the ecotone boundaries. The parameters of the BEDA model were adjusted according to non-linear least-square regression analyses conducted using the R 2.9.2 environment for statistical computing (R Development Core Team 2009). Analyses were only performed for days on which all fitted BEDA parameters were significant ( $P < 0.05$ ).

## RESULTS

High daily and inter-daily variation was observed for all of the studied microclimatic variables (T, RH and

VPD; see Appendix S1). The amplitude of the daily variation in the savanna was more than twice that for the forest, and was slightly higher during the dry season than during the humid season. For example,  $VPD_{\text{ampl}} = 0.25 \pm 0.24$  and  $1.19 \pm 0.65$  kPa during the humid season in the forest and savanna, respectively; the corresponding values for the dry season were  $0.50 \pm 0.29$  and  $1.66 \pm 0.70$  kPa.

Over the studied period, the microclimatic conditions in each of the three transects were very similar for both the savanna and the forest core (Fig. 2). The temperature and VPD increased during the dry season while the RH decreased. The amplitudes of these seasonal changes were relatively low, but the changes in RH and VPD were more pronounced on the savanna than in the forest. The mean temperature increased by around  $5^{\circ}\text{C}$  in both environments, whereas the RH decreased by 12% in the savanna compared with 7–9% in the forest and the VPD increased by 0.6 kPa in the savanna but only 0.3 kPa in the forest. For both the temperature and the relative humidity, the difference between the values measured in the savanna and the forest was relatively consistent over the studied period: the forest was generally around  $5^{\circ}\text{C}$  cooler than the



**Fig. 2.** Daily mean air temperature (T), relative humidity (RH) and vapour pressure deficit (VPD) values in the savanna (white circles) and forest (black circles) cores over the course of the study period, estimated using border and ecotone detection analyse (BEDA). The crosses show the difference between the mean values of the corresponding microclimatic variable for the savanna and the forest. The grey area indicates the expected duration of the dry season.

savanna and its relative humidity was around 20% higher. The difference in VPD between the two environments was somewhat more variable (Fig. 2).

Surprisingly, the positions of the ecotone borders estimated using BEDA were quite consistent for the three studied microclimatic statistics, with the exception of the savanna-side ecotone border in transect 2 (Figs 3,4). The estimated position of the boundary between savanna and forest based on microclimatic variables was shifted slightly towards the savanna (by around 2.5 m) compared with the boundary position determined based on field observations of vegetation structure and composition (which was located at 0 m by definition). The transitions of microclimatic conditions between savanna and forest were very sharp, with the microclimatic ecotones being around 5 m wide throughout the studied period in all cases save that of transect 2 during the wet season, where the width of the ecotone reached approximately 12.5 m and its boundary shifted towards the core of the savanna by about 5 m (Fig. 3).

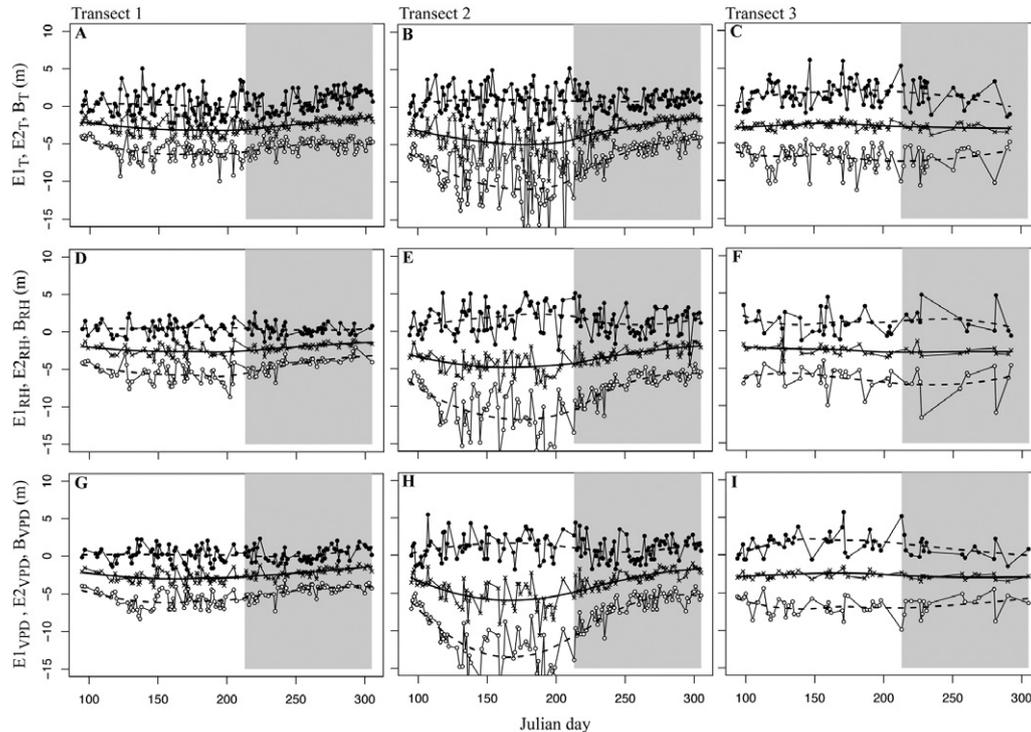
One of the most striking results obtained in this work was that the bulk of the microclimatic ecotone was located outside the forest on even the driest days (Fig. 4). In other words, microclimatic edge effects had relatively little impact at the forest border and drought severity increased quite homogeneously

throughout the forested region rather than having a disproportionately large impact close to the forest edge. This observation rejects our first hypothesis.

## DISCUSSION

Previous studies have monitored microclimatic conditions in regions featuring transitions from open landscapes (e.g. savannas) to forests in Africa (Hennenberg *et al.* 2008), South America (Didham & Lawton 1999; Hoffmann *et al.* 2011) and Oceania (Davies-Colley *et al.* 2000; Pohlman *et al.* 2009). However, to our knowledge, the data presented herein constitute with Little *et al.* (2012) in Australia, one of the longest continuous records of this type; the length of the studied period associated with the high sampling intensity in this work enabled us to simultaneously analyse the dynamics and the spatial structure of microclimatic edge effects.

Measurements of microclimatic variables along transects revealed a sharp transition between savanna and forest usually took place within the first 5 m outside the forest boundary. This transitional area was located just outside the boundary of the forest, in the savanna, as determined by field observations of vegetation cover and was characterized by moister



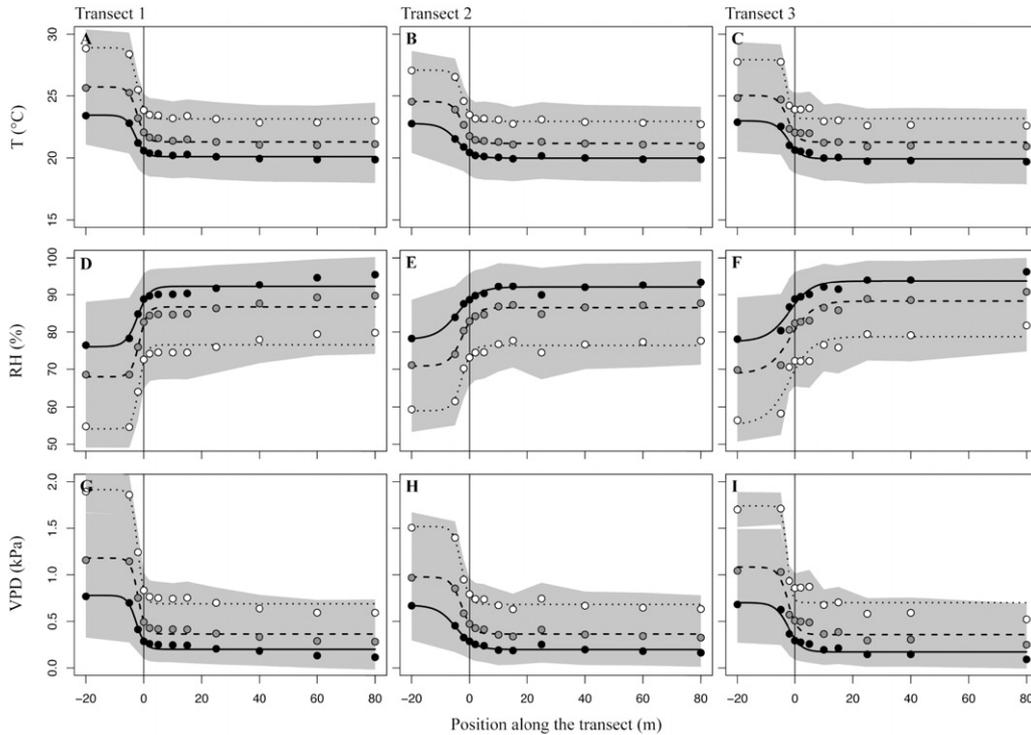
**Fig. 3.** Daily locations of the borders of the ecotone on the savanna side (E1, white circles) and on the forest side (E2, black circles), and the estimated position of the boundary between savanna and forest (B, crosses) estimated using border and ecotone detection analyse (BEDA) based on the air temperature (T), relative humidity (RH) and vapour pressure deficit (VPD). The grey area indicates the expected duration of the dry season.

conditions than those prevailing in the savanna. Relatively homogeneous microclimatic conditions were observed at all points within the forest boundary. This suggests that during periods of drought, the effects of the drought are distributed homogeneously within the forest and it does not have a disproportionate impact near the forest edge. This may account for the observation that when fires successfully spread within the edge of the forest, they are capable of spreading extensively within the forest, as recently observed in Amazonia (e.g. Cochrane & Laurance 2002; Alencar *et al.* 2004).

The microclimatic conditions at the forest–savanna boundaries are strongly dependent on the structure and composition of the vegetation within and around the border (Matlack 1993; Didham & Lawton 1999; Ray *et al.* 2005, 2010). For instance, the studies of Matlack (1993) and Didham and Lawton (1999) showed that microclimatic edge effects such as drought penetration are more pronounced at open edges than at closed ones. This suggests that the sharpness of the microclimatic ecotone between savanna and forest (which was about 5 m wide in this case) and the relative homogeneity of the microclimatic conditions along the forested part of the transect are due to: (i) the sharp transition in tree density, which increases over the space of a few metres from about 0.1 stems

per square metre in the savanna to 0.4 stems per square metre in the forest (Ibanez *et al.* submitted, 2012) and (ii) the fact that both the border and the forest core are composed of persistent tree species that form a closed canopy. Interestingly, using methods similar to those employed in this work, Hennenberg *et al.* (2008) found that the microclimatic ecotone for the border of a forest dominated by deciduous trees was around 100 m wide.

There is increasing evidence that the distribution of savanna and forest is shaped by fire and that the time post fire drives the structure and the composition of the vegetation with strong feedback loops on fire through fuel and microclimate modification (Staver *et al.* 2011; Hoffmann *et al.* 2012; Knox & Clarke 2012; Murphy & Bowman 2012). For instance, Hoffmann *et al.* (2012) showed that the tree leaf area index (LAI) increased with the time post fire while the grass LAI decreased. According to the same authors a tree LAI of 3 – called the ‘fire suppression threshold’ – suppresses the flammable grass layer, while a tree LAI of 3.5 significantly modifies the VPD in the undergrowth (Ray *et al.* 2010). In our case, fires in the savanna part of the transect are likely too frequent and prevent tree establishment, thus tree cover remained low and does not modify the microclimate. Conversely, on the forest part of the transect, time post fire



**Fig. 4.** Mean daily air temperature ( $T$ ), relative humidity ( $RH$ ) and vapour pressure deficit ( $VPD$ ) values measured by the data loggers along the three transects during the expected humid (black circles) and dry (grey circles) seasons, as well as for the 10% hottest and driest days (white circles). The grey area covers one standard deviation, and the full, dashed and dotted lines delineate the border and ecotone detection analyse (BEDA) fits. The vertical line represents the boundary between the savanna and the forest as determined from field observations.

was likely long enough to reach the ‘fire suppression threshold’ (likely several decades), tree cover is high forming a continuous canopy, the grass layer is absent and the microclimatic conditions are very different from those prevailing into savanna.

Our results suggest that during the studied period, savanna fires would not penetrate into the forest understorey because of the strong difference in forest microclimate. Indeed, according to Ray *et al.* (2005) the spreading of fires into the forest understorey is strongly inhibited when the  $VPD$  is less than 0.75 kPa, a threshold that was only surpassed during the very driest days in this study. This hypothesis was further supported by field observations of savanna fires, which clearly stopped before reaching the forest edge during the studied period (Ibanez, pers. obs., 2010). Nevertheless, it is important to note that at global and regional scales, climate variability related to *El Niño* Southern Oscillation (ENSO) phenomenon has a strong effect on the spatiotemporal variability of fire regimes (Fuller & Murphy 2006; Le Page *et al.* 2008; van der Werf *et al.* 2008). For instance, Alencar *et al.* (2004) showed that in eastern Amazonia, fires related to droughts induced by *El Niño* accounted for more than 90% of the total forest area burned between 1982 and 1999. In New Caledonia, recent studies (Barbero

*et al.* 2011; Moron *et al.* 2012) showed that the number of fires and the burned area are closely related to the austral spring (September–November) rainfall anomalies, the last ones being driven by the ENSO phenomenon. According to the same authors, the year studied here (2010), was relatively humid due to a relatively intense *La Niña* episode and exhibited a relatively low amount of fires. Hence, we suggest that during driest years such as those during *El Niño* periods, the increase in drought in the forest understorey makes the forest edge more vulnerable to savanna fires. Moreover, we can not exclude that in keeping with the findings of Hennenberg *et al.* (2008), the microclimatic ecotone between the savanna and the forest might shift towards forest.

The focus on one boundary allowed us to intensively monitor microclimate and to accurately describe the spatiotemporal dynamics of edge effects. Nevertheless, given the close proximity of our transects, we acknowledge that although the studied boundary is representative of savanna–forest boundaries sharpened by frequent fires (Ibanez 2012), the generalization of our results suffers from a lack of true replications (see Murcia 1995). Further studies are needed to assess the importance of other factors such as the orientation of the boundary or its topographical position.

## CONCLUSION

Contrary to our hypothesis, the microclimatic ecotone between the savanna and the forest was located outside the forest throughout the studied period. The effects of the drought are distributed homogeneously within the forest and it does not have a disproportionate impact near the forest edge. In contrast, the savanna area located just outside the boundary of the forest was characterized by moister conditions than those prevailing in the savanna core. Under such conditions, the vulnerability of the forest edge to savanna fires should be relatively low and relatively wet conditions in the savanna close to the forest edge may promote forest expansion by limiting fire spread. Nevertheless, during abnormally dry years (i.e. during *El Niño* episodes) we suggest that the increase in drought in the forest understorey makes the forest edge more vulnerable to savanna fires. Such conditions might also increase the number and intensity of savanna fires, further amplifying the forest's vulnerability (Barbero *et al.* 2011). Given that suppression of fire in New Caledonia seems unrealistic, prescribed burning of the savanna during humid years could potentially allow reduction of savanna fuel loads with relatively low risk of fires penetrating the forest edge, which might be useful in ensuring that the forest is not severely affected by fire during dry years.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Appendix S1.** Hourly air temperature, relative humidity and vapour pressure deficit during the study period.