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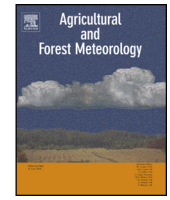

Higher tree transpiration due to road-associated edge effects in a tropical moist lowland forest

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ABSTRACT

Newly created forest edges have significant ecophysiological effects on bordering trees. We studied edge effects on microclimate and tree transpiration rates during wet and dry seasons along a 250 m transect spanning the edge of an unpaved road into an old growth tropical lowland forest in the Central Brazilian Amazon. Canopy openness decreased only minimal from the road (3.68%) towards the forest interior (1.69%). Vapor pressure deficit (measured at 2.2 m height above ground) was lower in the forest interior. The edge effect on microclimate penetrated deeper into the forest (>100 m) during the dry season compared to the wet season (<100 m). Overall, sap flux, and therefore transpiration rate, was 54% higher in trees adjacent to the road compared to forest interior trees. Higher transpiration rates at the forest edge can be explained by higher turbulences and energy exchange of the canopy boundary layer and by a shift in species composition to high water using secondary forest species 25 years after the road construction. Similar changes might be expected for other disturbances affecting local relative humidity and in situations that favor plants with water use traits differing from those found in the forest interior.

1. Introduction

Tropical forests play a key role in the global climate system (Laurance, 1999) and are among the world's hotspots in sustaining biodiversity (Lowman et al., 2006). Despite the manifold environmental services that tropical forest provide, the rate at which remaining pristine forest is lost remains high and worldwide, tropical landscapes become increasingly fragmented (Laurance et al., 2006). In many cases the construction of roads plays a key role in deforestation (Laurance et al., 2001b), since roads provide access for logging or conversion of forest to other land uses. Even if land conversion around the road is minimal, certain road-associated physical and ecological edge effects on the adjacent forest can be expected (Forman and Alexander, 1998; Laurance et al., 2009). Roads are effectively narrow but very long forest gaps creating contrasting meso- and micro-climatic conditions compared to the neighboring forest (Laurance et al., 2009). Better understanding the edge effects caused by roads might help to reduce the negative effects of road networks on already stressed ecosystems (Delgado et al., 2007).

The creation of forest edges, of which roads are a subset, has numerous abiotic and biotic effects on the remaining forest (Harper et al., 2005; Laurance et al., 2002). These sharp boundaries alter the forest climate locally, with increased diurnal amplitude for temperature, humidity, radiation, wind speed close to the forest edge and advection energy (Ewers and Banks-Leite, 2013; Roberts and Rosier, 2005; Turton and Freiburger, 1997). This exposure and change in microclimate conditions results inevitably in an alteration of many tree physiological processes and forest structure in the short term, and forest species composition in the long term (Laurance et al., 2002; Ramos et al., 2013). The intensity of those effects depends on the physical contrast with the adjacent habitat and how the forest edge is structured (Didham and Lawton, 1999). Furthermore, the intensity of effects is expected to decrease over time as forest edge structure changes and some regrowth occurs in cleared areas (Ewers and Banks-Leite, 2013).

Most studies to date have focused on edge effects associated with large deforested blocks where forest vegetation may

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Table 1
Summary of species names and characteristics of study trees.

Species	Family	Subplot	DBH (cm)	Ac (m^2)	Height (m)	Successional state
Licania sp.	Chrysobalanaceae	10 m	27.6	159	22	late secondary[a]
Pourouma bicolor Mart.	Moraceae	10 m	24.5	53	21	pioneer[b]
Micropholis guyanenis duckeana (Bahni) T.D. Penn.	Sapotaceae	10 m	22.0	87	17	late secondary[a]
Caryocar glabrum (Aubl.) Pers.	Caryocaraceae	10 m	19.5	32	13	late secondary[a]
Protium apiculatum Swart	Burseraceae	10 m	17.6	27	18	late secondary[a]
Pouteria cladantha Sandwith	Sapotaceae	10 m	22.8	31	22	late secondary[a]
Eschweilera wachenheimii (Benoist) Sandwith	Lecythidaceae	50 m	23	84	19	climax[c]
Euphorbiaceae *sp.*	Euphorbiaceae	50 m	17.2	Tree crown broke during the study		
Jacaranda copaia (Aubl.) D. Don.	Bignoniaceae	50 m	25.7	68	24	pioneer[a]
Protium pallidum Cuatrec.	Burseraceae	50 m	20.8	101	21	late secondary[a]
Eschweilera wachenheimii (Benoist) Sandwith	Lecythidaceae	50 m	17.5	40	20	late[c]
Eschweilera truncata A.C.Sm.	Lecythidaceae	50 m	17	34	18	late[c]
Tachigali paniculata Aubl.	Fabaceae	100 m	34.2	138	27	late secondary[d]
Tachigali paniculata Aubl.	Fabaceae	100 m	23.8	93	24	late secondary[d]
Eschweilera wachenheimii (Benoist) Sandwith	Lecythidaceae	100 m	21.3	41	20	climax[c]
Protium hebetatum D.C. Daly	Burseraceae	100 m	23.9	92	22	late secondary[e]
Minquartia macrophylla Ducke	Olacaceae	100 m	25.9	93	25	climax[c]
Virola calo phylla (Spruce) Warb.	Myristicaceae	100 m	19.7	47	23	late secondary[f]
Licaria crassifolia (Pior.) P.L.R. Morales	Lauraceae	250 m	26.5	75	26	late[e]
Virola calophylla (Spruce) Warb.	Myristicaceae	250 m	18.6	30	23	late secondary[f]
Corythophora alta R.Knuth	Lecythidacea	250 m	44.0	259	28	late[f]
Pouteria retinervis T.D.Penn.	Sapotaceae	250 m	21.3	37	25	late secondary[e]
Pouteria erythrochrysa T.D.Penn.	Sapotaceae	250 m	19.7	57	26	late secondary[e]
Plethogyne catingae Duke	Fabaceae	250 m	48.5	242	26	late[f]

[a] Amaral et al. (2009).
[b] Basset (2001).
[c] genus classified in Swaine and Whitmore (1988).
[d] genus classified in Peña-Claros (2003).
[e] genus classied in Marra et al. (2014).
[f] classified by our field botanist following the criteria of Kammesheidt (2000).

be replaced with other kinds of plants (e.g. pasture grasses), but the area is still vegetated (Chen et al., 1995; Giambelluca et al., 2003; Laurance et al., 2002). Road-associated edge effects are much less explored (Dambros et al., 2013), and differ in several ways, including the lateral extent of the clearing which is smaller but permanent, and the fact that roads remain unvegetated. In general, forest edges situated downwind of a contrasting habitat are expected to show higher evapotranspiration rates (Giambelluca et al., 2003). Most evidence to date is derived from indirect measurements such as soil water content (Kapos, 1989) and show edge-related influence on microclimate and soil moisture extending 20 up to 100 m into the remnant forest (Davies-Colley et al., 2000; Ewers and Banks-Leite, 2013; Laurance et al., 2002). Differences in the area influenced by edge effects have been related to the degree of contrast between the adjacent habitat, the size of the forest patch and the time elapsed since the change in forest structure (Harper et al., 2005).

Although large-scale edge effects of >1 km appear to have been detected with remote sensing technology along the eastern Amazon deforestation frontier (Briant et al., 2010), effects of edges on tree transpiration rates remain largely unexplored, especially next to roads. However, the few existing ecophysiological studies on edge effects reveal a significant enhancement of tree water use due to the forest edge (Giambelluca et al., 2003; Herbst et al., 2007; Ringgaard et al., 2012; Wright et al., 2012). To our knowledge no previous study exists evaluating the ecophysiological response of trees growing next to a road in the tropics. Here, we explore road-associated edge effects on spatial variations in microclimate and tree transpiration rates in a tropical lowland forest close to Manaus in the Central Amazon. Our objectives were to determine (1) the effects of a road on the microclimate within an adjacent old growth forest, (2) how tree transpiration rates differ with distance to the road, and (3) if there are variations in the intensity of edge effects between the dry and wet seasons.

2. Material and methods

2.1. Study site

The study area is located approximately 60 km to the north west of Manaus, Brazil (02°38′22.54″S 60°09′51.34″W). A climate station located 25 km from the study sites shows that average rainfall in the area averages 2550 mm y^{-1}. There is a short dry season (defined as consecutive months with <100 mm rainfall) of one month in August, though monthly rainfall can also be below 100 mm in months between June and October. Average annual air temperature is 25.8 °C and varies little between months. The terrain in the study area has an undulating topography, with high-clay Oxisols dominating on plateaus, whereas in the riverbeds a sand rich Spodosols are the dominant soil type. The natural vegetation on plateau areas is well-drained species-rich evergreen tropical moist forest (*terra firme*) with usually over 250 tree species per hectare (trees ≥10 cm in diameter) and seasonally inundated tropical moist forest (*igapó*) with lower species richness in the valley streams.

The study site is along the access road to the field station for forestry management of the Brazilian National Institute for Research in the Amazon (INPA) at the kilometer mark 18. The access road is ~6 m wide and was built in the 1980s and is maintained yearly, including an approximately 9 m wide buffer zone to avoid blocking of access by falling trees. The total distance from forest edge to forest edge measures approximately 24 m. Average canopy height in the area is 28 m, however canopy trees growing next to the road were not as tall as in the forest interior (compare Table 1). At the study site, the road trends from East-northeast to West-southwest and transects a large plateau of approximately 1.4 × 1.0 km area. A transect was marked perpendicular to the road and extending 250 m south-southeast into the forest, starting at the forest edge and ending in the middle of a one hectare monitoring plot (Fig. 1). Subplots of 20 × 50 m were established along the transect between 0 and 20 m, 40 and 60 m, 90 and 100 m and 240