Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands)

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Abstract

The estimation of the road edge effect is useful to understand changes induced by the road network on ecosystems. Road networks on islands may break ecosystem integrity through microclimate edge effects, which are known to be associated with disturbances to animal and plant communities. Road edge effects have been scarcely studied on oceanic islands. In this paper we studied road edge effects on microclimate and canopy structure in laurel and pine forests in Tenerife (Canary Islands). We assessed depth of road edge effect for temperature at four vertical layers (soil, litter and air at 5 cm and 1.3 m above ground), light intensity, canopy cover and height, in transects running from narrow (6–7 m width) asphalt roads and dust trails to 100 m to the interior of both forests. We used an ANOVA procedure with Helmert difference contrasts to identify the distances along transects over which edge effects were significant. We detected significant gradients for most parameters but they were consistently narrow both within and between forests. In the laurel forest, we detected highly significant gradients for soil temperature, light, and canopy cover and height in both asphalt and unpaved roads. In the pine forest, we detected a highly significant gradient for soil temperature at asphalt roads, and a significant light gradient for both asphalt and unpaved roads. From the road edge to the forest interior, significant temperature changes persisted for only 3 m, light variation persisted for 6 m, and canopy cover and height changed significantly within the first 10 m. Asphalt roads and dust trails revealed different patterns of variation for temperature between edge and interior. No differences were found between the two types of roads in edge-interior trends for light or canopy structure. The abruptness of microclimate and canopy gradients was slightly higher in the laurel forest than in the pine forest, caused by a higher edge contrast in the former. The depth of the road edge effect found in laurel and pine forests was small, but it could have cumulative effects on forest microclimate and forest associated biota at the island scale. Such changes deserve attention by local road managers for planning and design purposes.
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1. Introduction

Undoubtedly, roads play a key role in urban and suburban development, facilitate movements of human population over the land, and connect societies and economies (Havlick, 2002). However, at the same time, roads generate many collateral problems for the conservation of ecosystems (Spellerberg, 1998; Trombulak and Frissell, 2000; Forman et al., 2002; Song et al., 2005) and landscape integrity (Jaarsma and Willems, 2002, Serrano et al., 2002). Roads create micro and mesoclimatic changes and probably contribute to global macroclimate change, through variation of the received sun radiation, wind regimes, moisture and temperature (Forman et al., 2002). Depending on the traversed ecosystem, road impacts on microclimate, vegetation and fauna can vary widely. For example, forest roads create linear gaps that remove forest area, divide the ecosystem and create structural edges where abiotic and biotic conditions change more abruptly than in open bushland (Forman and Alexander, 1998; Spellerberg, 1998; Trombulak and Frissell, 2000). In forested areas, the forest matrix dominates the landscape, but roads remove or disturb large areas through indirect effects that accumulate and interact at higher scales (Theobald

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et al., 1997; Forman, 1998; Heilman et al., 2002; Saunders et al., 2002; Riitters and Wickman, 2003). Disturbances on abiotic variables can extend variable distances beyond the road gap (Williams-Linera, 1990; Young and Mitchell, 1994; Laurance et al., 1997), and microclimate edge effects have been shown to extend to the surrounding habitats from only a few meters up to hundreds of meters (see examples in Forman et al., 2002). Therefore, the estimation of the road edge effect for abiotic variables is a useful tool to assess the amount of territory that is functionally affected by the road network (Forman and Deblinger, 2000). Concretely, the identification of underlying abiotic gradients that percolate the fragmented ecosystem is a necessary step to understand road influence upon ecosystem structure and dynamics (Forman and Alexander, 1998).

Oceanic islands worldwide are being heavily changed and constrained by urbanization and transportation pressures (Whittaker, 1998; Fernández-Palacios et al., 2004; Song et al., 2005). The Canary Islands have the highest road density of all the European islands, 6 km km^{-2} (Martín and Fernández-Palacios, 2001). In Tenerife, the road network occupies 3% of the island area, but this is a conservative figure based only on paved roads mainly on non-protected territory. The Canarian laurel and pine forests are traversed by a dense network of corridors including paved and unpaved roads, fire-breaks and powerline clearings, which have received little attention as ecological and landscape elements (Martín and Fernández-Palacios, 2001).

Previous studies have evaluated microclimatic differences between laurel forest natural gaps and interior revealing large differences in global radiation, photosynthetically active radiation (PAR), temperature, wind speed, and relative humidity (Aschan et al., 1994; González-Rodríguez et al., 2001). No study was available for the Canarian pine forest. Apparently, no previous work has been devoted to differences between road gaps and forest interior in both laurel and pine forests in the Canary Islands.

An evaluation of the ecological edge effects of the transportation infrastructure is urgent for the Canarian archipelago and for many other oceanic islands. Roads and associated structures are transforming amounts of territory probably far larger than expected by local environmental authorities. Local managers rely on mostly subjective and partial environmental impact assessments that do not consider road edge effects, the fragmentation process implied, and the specific damages to habitats and the biota (Byron et al., 2000).

Microclimate gradients across road edges influence many ecological processes and patterns. Abiotic gradients reaching the forest interior from the road may transform a large amount of forest into suitable habitat for exotic plants (Fraver, 1994; Goosem and Turton, 2000) and animals (Didham et al., 1998). Floristic composition changes more or less suddenly along such gradients (e.g. Landenberger and Ostergren, 2002; Hansen and Clevenger, 2005).

In the laurel forest, forest destruction by roads and other structures causes progressive vegetation degradation, with the new open spaces being concealed by shrubs, bracken ferns and numerous introduced Mediterranean elements (Höllermann, 1981). Numerous exotic plants are increasingly colonizing for-

est road edges in the Canary Islands (González and González, 2001; Arévalo et al., 2005). However, most exotic plants and many sun-loving native ones are apparently limited to narrow (1–5 m) open roadsides. Probably, microclimatic changes produced in the zone of road edge effect are favoring the spreading of exotics outward the road surface in the Canarian forests and other habitats (Arévalo et al., 2005).

Forest road edges in the Canaries also shelter high plant diversity and an important degree of endemism, especially regarding native edge-species and light-demanding ones. At the regional scale, roads would promote native sun-loving elements, since natural treefall gaps occur at very low frequencies in the Canarian laurel forest (Arévalo and Fernández-Palacios, 1998).

Regarding non-native animals, introduced ship rats use more frequently laurel and pine forest road edges than the forest interior when foraging (Delgado et al., 2001), and are also strong nest predators along and near roads (Delgado et al., 2005). Endemic lizards (*Gallotia galloti*) were more abundant along road edges than at the interior of both forests (Delgado et al., in press). Roads were thought to play a probable role as corridors through inhospitable forest matrix for these lizards, changing natural patterns of abundance, distribution and population genetic variation at the island scale. In some laurel forest patches, these heliothermic lizards are found only in a narrow stretch of forest outward the road surface where microclimatic requirements are met (Delgado et al., in press). If important ecological components (i.e. decomposers, top predators, pollinators) change relative abundances due to microclimate changes caused by roads, changes in key ecological processes can be expected to start alongside roads (i.e. changes in decomposition rates of necromass, predator–prey relationships, or plant–animal mutualisms) (Giller, 1996; Hansson, 2000). The interpretation of such biotic disturbances initiated at road gaps would benefit from knowing the underlying abiotic gradients.

In this paper, we evaluate microclimatic and structural gradients from roads to forest interiors. Along transects perpendicular to roads in both laurel and pine forests, we measured: (a) temperature at ground level, leaf-litter level, and two heights above ground; (b) light intensity; (c) canopy cover and height. Our goal was to determine if gradients in these variables differed for paved and unpaved roads, and between laurel and pine forests.

2. Study area

The field work was conducted on the laurel and pine forests of Tenerife (Canary Islands, 27–29°N, 13–18°W). Laurel forest sites are located on the Anaga mountains within the limits of the Parque Rural de Anaga, in the Anaga massif, NE Tenerife (700–1000 m asl) (Fig. 1). The pine forest sites are included in the Parque Natural Corona Forestal and Paisaje Protegido Las Lagunetas, along the dorsal road between La Esperanza and the Parque Nacional del Teide (~1000–2000 m). The asphalt road segments studied have average daily traffic densities (mainly tourism particular cars and buses) of 253–1317 vehicles (laurel forest) and 1536–2460 vehicles (pine forest) (Anon, 2004).

The laurel forest has a diverse tree canopy averaging 9–10 m in height (reaching up to 15–20 m in forest basins) and 80% cover. Dominant trees are *Laurus azorica*, *Myrica faya*, *Erica arborea*, *E. platycodon*, *Ilex canariensis* and *Prunus lusitanica*. Less frequent trees are *Persea indica*, *Apollonias barbujana*, *Picconia excelsa*, and *Ilex perado*. The understory (2–4 m height) is dominated by *Viburnum rigidum*, ferns, and tree saplings and sucklings. In the Anaga laurel forest, mean annual and absolute monthly maximum temperatures are 13.7 and 20.6 °C, respectively, whereas minimum temperature was 8.5 °C (Eguchi et al., 1999). Mean annual relative humidity is 87–89%, decreasing to 40% outside the canopy in August (Eguchi et al., 1999). Annual precipitation is 900–1000 mm, with five dry months per year and the wettest month with a precipitation above 200 mm (Höllermann, 1981; Marzol, 1988).

The Canarian pine (*Pinus canariensis*) forest has a 20–30 m canopy height (sometimes up to 40 m) with 60% cover. The understory is sparse and formed by *M. faya*, *E. arborea*, *Chamaecytisus proliferus*, *Adenocarpus foliolosus*, *Daphne gnidium*, *Cistus* spp., and *Lotus campylocladus*. In the pine forest, mean annual temperature is 13.8 °C, with maximum in August (20.6 °C) and minimum in January (9.2 °C). Maximum and minimum absolute monthly temperatures range between 20.6–36.6 °C and 0.2–8 °C, respectively. Annual precipitation is 900–1070 mm, with maximum in January and December (137–176 mm) (Marzol, 1988; Blanco et al., 1989).

3. Methods

3.1. Transect selection

In order to minimize the influence of topographic landscape controls on local microclimate, we restricted the sampling to sites with these requisites: (1) as similar elevation as possible (altitudinal limits between transects: laurel forest, 790–980 m; pine forest, 1065–1400 m; maximum altitudinal range in which forests develop: ~1000 m); each individual transect was completed within 100 m elevation between the edge and the extreme at forest interior; (2) similar aspect (all hillsides in laurel forest, but one that was north-faced, were S, SW or SE; all hillsides in pine forest faced S, SE or SSE); (3) low variation in microtopography (e.g. absence of large boulders or rocks) and slope; (4) similar corridor width (~6–7 m in all trail and road segments) and straight in shape; (5) lack of recent human disturbances such as wood, foliage or litter removal; (6) no overlapping with other linear infrastructures such as fire breaks, powerline corridors,
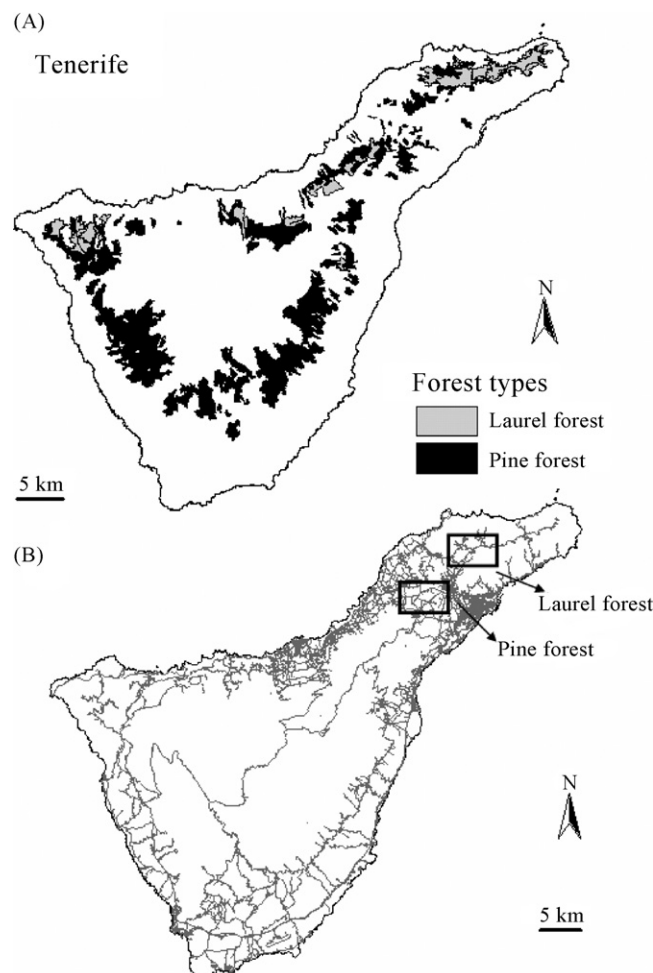

Fig. 1. Map of the study areas in Tenerife (Canary Islands): (A) the Tenerife laurel and pine forest remnants; (B) the Tenerife main paved road system and the two study sites (rectangles); (C) location of transects in pine forest; (D) location of transects in laurel forest.
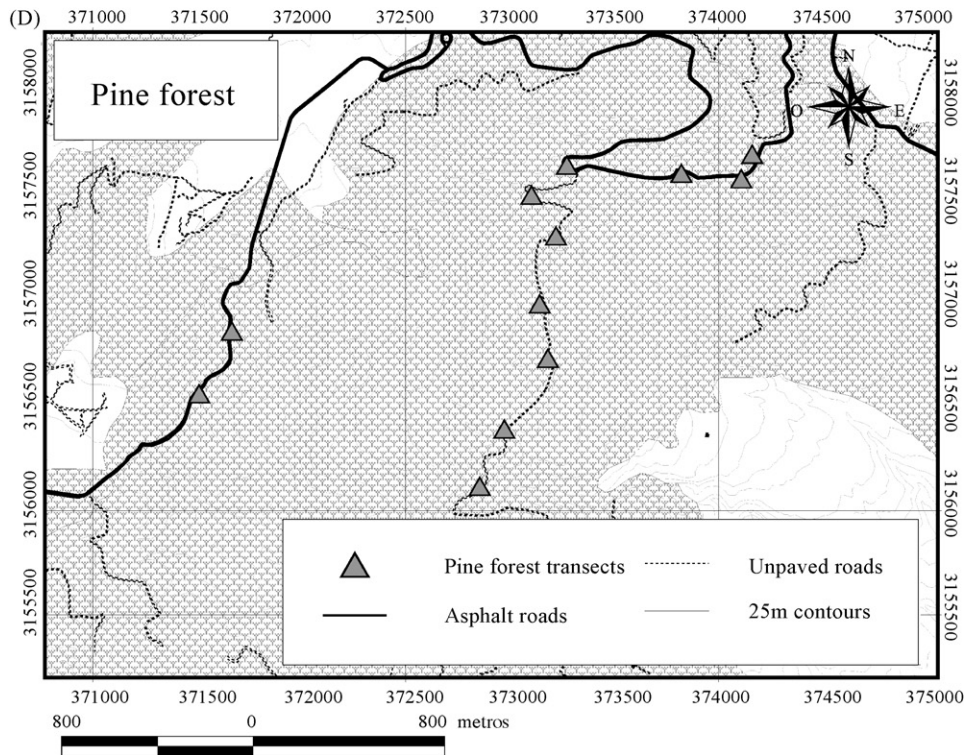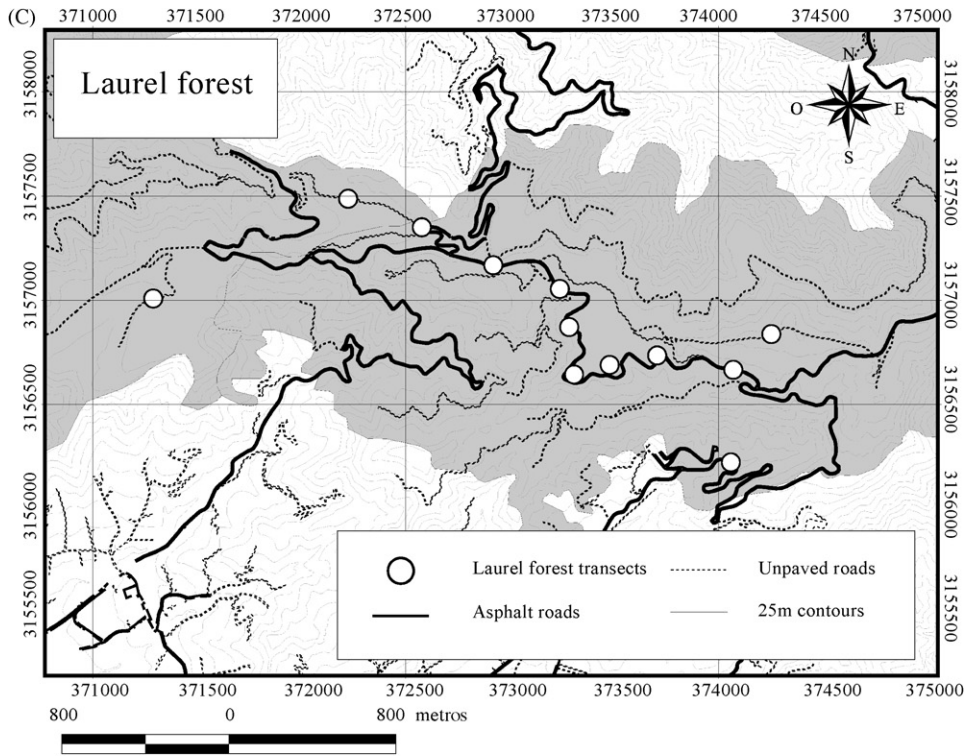
Fig. 1. (*Continued*).

habitation areas or areas of strong relief (i.e. deep ravines or slopes).

With these restrictions, we constructed transects at right angle from the road edge to the forest interior. We alternated transects between upslope and downslope directions from the road. We established 13 transects in laurel forest (9 in asphalt road, 4 in dust trail) and 12 transects in pine forest (6 in asphalt road, 6 in dust trail), for a total of 25 transects. We considered the edge as the outer limit of the artificial road surface (asphalt for paved roads or earth pavement for trails).

We placed ten sampling points along each transect at the following distances from the edge, in meters: −3 (roadway center), −1 (roadway side), 1, 3, 6, 10, 20, 40, 60 and 100, for all variables excepting leaf-litter temperature (negative distances are on the road surface, positive distances are inside the forest). Leaf-litter was virtually absent within the roadway so the transect for this variable started within the first meter from the roadway edge.

Laurance et al. (1997) pointed out that, excluding wind, most abiotic edge effects are commonly produced within 100 m of any edge. Our 100 m-long transects were a compromise between the trend to overestimate or underestimate (fail to find a net pattern) the potential edge effects (Laurance, 1991). It was also difficult to find sites with no other overlapping edges or different forest types further than 100 m from roads. Transects were at least 100 m apart to study different edges and to minimize spatial autocorrelation and pseudoreplication at the landscape scale (Honnay et al., 2002).

3.2. Microclimate and canopy data

Abiotic data were taken once at each sampling point on each transect between March and June 2003 in both forests. This period comprised a small transition in air temperature at 1.3 m above ground, with a maximum difference of 2.5 °C in both forests. The overall climate is highly buffered by the trade winds and the presence of the orographic cloud layer over this period. Hence, we assumed that this temporal variation did not change substantially the overall spatial pattern of edge effects. On each transect, data were collected within 1 h between 1200 and 1500, period with maximum values of sun radiation and temperature, minimum relative moisture, and the highest parameter stability (Höllermann, 1981; Rosenberg et al., 1983; Marzol, 1988; Aschan et al., 1994). More than one transect could be completed between 1200 and 1500 the same day. We avoided working on rainy, cloudy or windy days.

Temperature was measured with a digital thermo-couple (Heraeus, Germany; error: ±1 °C, precision: ±0.1 °C) in the following layers: soil (∼5–10 cm depth at interior forest), leaf litter, and air at two heights above ground (5 and 130 cm). We recorded temperature of the surface of asphalt (paved roads) and compacted earth (dust trails).

Sunlight exposure of the understory was estimated with a digital hand lux meter (Delta Ohm Light meter HD8366, Italy; illumination measure: lux; range: $0.1–2 \times 10^{-5}$ lx; 1 lx = 1 lumen m^{-2}) at 1–2 cm above the forest ground. The forest floor actually behaves as a light mosaic due to continuous opening and movement of the canopy (Canham et al., 1994). Due to this, any given point selected on the ground receive different amounts of light within brief time lapses. To cope with this punctual variation and the spatial patchiness, 4 readings were haphazardly distributed on a 6 m-length sub-transect at right angle with the main transect, and at every distance from the edge, and the mean value was calculated and used in the analysis.

Due to absence of nearby meteorological stations, we could not collect continuous light and temperature data near from the transects to check whether the gradients were related to daily variation or to edge effects. However, some lines of evidence

support actual edge-to-interior gradients in microclimate, and not daily oscillations. This is a period of maximal stability in microclimatic parameters (Höllermann, 1981). Microclimatic variables were measured nearly simultaneously by two-three persons on different distances on each transect. As pointed out above, all individual transects were completed within 1 h in the interval 12:00–15:00 local time, and more than one transect could be completed within this period. In addition, in laurel forest, global radiation, illumination and photosynthetic active radiation (PAR) experience minimum variation throughout the day near the shaded ground, where thermal extremes are mild (Höllermann, 1981). In July, maximum illumination at our study area (900–950 m elevation) was found to range 115,000–120,000 lx between 12:00 and 15:00 h outside the laurel forest canopy, but it was only 6000 lx at the forest floor (Höllermann, 1981). Third, the variation in sunlight and temperature in spring-early summer is minimal in the Canaries, especially below the forest canopy at least in the laurel forest (Höllermann, 1981, 1982), but probably also in the pine forest. Daily soil temperatures are stable (12.5 °C in May) between 1000 and 2400 h in the laurel forest (Höllermann, 1981, 1982). Finally, due to its latitude (28° N, ∼500 km north of the Tropic of Cancer), the solar midday occurs at 1400 h in the Canaries, and the change in luminosity between 1200 and 1500 is negligible on clear days for most of the study period.

We measured canopy height and cover at each sampling point. Canopy plus upper understory cover was estimated with a spherical forest densiometer as percentage (Robert E. Lemmon, Bartlesville, OK, USA; Lemmon, 1957). The densiometer was held at 1.5 m height and about 30 cm at right angle from the body and level. We counted the number of grid squares filled more than 75% (or 3/4) with tree reflections and obtained the percentage of closure over the total number of squares. Canopy height was estimated visually by the same person to the nearest 2 m from four sectors of a 5 m radius circle, centered on each sampling point, and the four measures were averaged.

3.3. Data analysis

We used ANOVA with a Helmert procedure to estimate the depth of the thermal, light and canopy structure gradients (Fraver, 1994; Burke and Nol, 1998). Other techniques to delineate edge effects have proven to be useful as well (see e.g. Zheng and Chen, 2000; Harper and Macdonald, 2001). The Helmert contrast compares, for a given variable across all transects, the mean value at the edge with the mean value at each successive distance from the edge. We tested for significant differences until the distance beyond which no significant changes appeared, using the Bonferroni post hoc contrast to correct the critical p-level for multiple comparisons. The main advantage leading us to select Helmert contrasts over other methods of mean or first differences is that it avoids serial correlation and maintains the homogeneity of variance between treatments, which was a requisite for our analysis (Bauer, 1997). In addition, the chance of serial correlation in our ordered data (serial measures along edge-to-interior transects) strongly recommended a multiple comparison method such as Helmert's (Bauer, 1997).

The edge reference level for the contrast was established at the centre of the roadway (-3 m). The results do not vary for purposes of the Helmert test if the opposite (100 m to the forest interior) is used. Due to the virtual absence of litter on the roadway, litter temperature was measured only after 1 m from the road margin towards the interior forest.

We also examined the effect of road type (dust trail versus asphalt road) on the gradients of microclimate and canopy structure with ANOVA with type III sum of squares for unbalanced design. We averaged values for the target variables described above per forest and road type. Before analysis, temperature, light and canopy height were $\log_{10}(x+1)$ transformed

to fulfil the parametric requisites to meet the assumption of normality. The analyses were performed in SPSS 11.0 (SPSS, 2001).

4. Results

4.1. Temperature

The temperatures measured at the four vertical strata showed overall decreasing trends from edge to interior in both laurel and pine forests (Fig. 2). In the laurel forest, we detected highly significant gradients of soil temperature in both asphalt
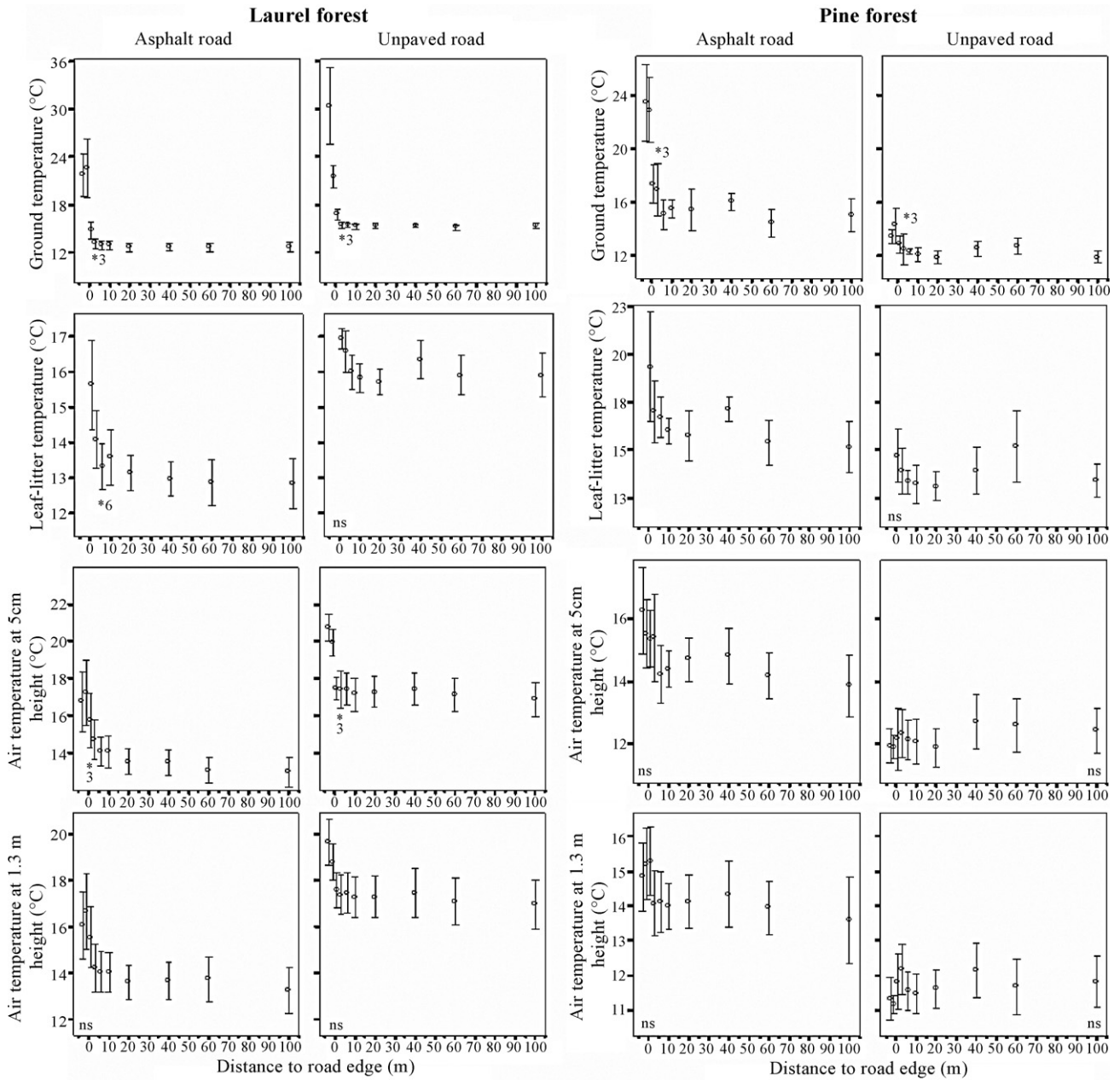

Fig. 2. Variation in temperature at four vertical layers from asphalt roads and dust trails to the interior of laurel and pine forests. Negative distances are on the road right-of-way, except for leaf-litter temperature. Shown are mean ± 1 S.E. (vertical bars). Asterisks denote the distance-to-edge beyond which no significant effect is detected.

Table 1
ANOVA tests of road edge effects on the abiotic variables

Variable	Distance to road (m)	Temperature (°C)				Light (klx, ground level)	Canopy	
		Soil	Litter	Air (5 cm height)	Air (1.3 m height)		Cover (%)	Height (%)
Laurel forest		Asphalt road						
	SS	0.578	0.038	0.113	0.067	18.802	25118.850	6.925
	Df	9	7	9	9	9	9	9
	MS	0.064	0.005	0.013	0.007	2.089	2790.983	0.769
	F	**6.239**	1.125	1.364	0.806	**10.735**	**12.075**	**11.636**
	P	**0.000**	0.360	0.220	0.612	**0.000**	**0.000**	**0.000**
		Unpaved road						
	SS	0.325	0.003	0.034	0.014	9.317	24891.293	3.975
	df	9	7	9	9	9	9	9
	MS	0.036	0.000	0.004	0.002	1.035	2765.699	0.442
	F	**15.693**	0.684	2.070	0.731	**13.850**	**44.639**	**73.249**
	p	**0.000**	0.684	0.065	0.678	**0.000**	**0.000**	**0.000**
Pine forest		Asphalt road						
	SS	0.282	0.039	0.021	0.015	1.086	4237.855	0.020
	df	9	7	9	9	9	9	9
	MS	0.031	0.006	0.002	0.002	0.121	470.873	0.002
	F	**3.464**	0.793	0.488	0.363	**2.292**	2.073	0.111
	P	**0.002**	0.598	0.876	0.947	**0.031**	0.051	0.999
		Unpaved road						
	SS	0.030	0.016	0.005	0.007	2.214	7936.857	0.584
	Df	9	7	9	9	9	9	9
	MS	0.003	0.002	0.001	0.001	0.246	881.873	0.065
	F	1.109	0.326	0.155	0.232	**2.202**	1.904	1.256
	P	0.374	0.938	0.997	0.988	**0.034**	0.069	0.280

SS: Sum of squares; df: degrees of freedom (10 distances to road except for leaf litter temperature, with only 8 distances); MS: quadratic mean or root mean square; p: significance level, set at $\alpha = 0.05$; significant F tests are shown in bold.

and unpaved roads (Table 1, Fig. 2). We did not detect an overall significant trend for litter or air temperature at the two heights above ground. In the pine forest, we detected a highly significant gradient for soil temperature at asphalt roads, but litter and air temperatures did not show overall significant trends.

We recorded a higher stability in mean soil temperature at the interior of both forests compared to the road edge or the road centre (Fig. 2). From the laurel forest interior (at 100 m) outward to asphalt and dust trails, soil temperature experienced average increases of 10 °C and 15 °C, respectively (Fig. 2). In the pine forest, the increases were comparatively lower (9 °C for asphalt roads and 1–2 °C for dust trails; Fig. 2).

The individual Helmert difference contrasts indicated the distance-to-edge at which the parameters became stabilized (Table 2). In the laurel forest, soil and air temperature at 5 cm became stable at 3 m from the edge of both asphalt and unpaved roads ($p > 0.05$; Table 2, Fig. 2). Litter temperature become stable at 6 m from the edge of asphalt roads and did not change significantly for unpaved roads. No significant edge effect was detected for air temperature at 1.3 m height in both road types ($p > 0.05$).

In the pine forest, soil temperature stabilized significantly at 3 m for both asphalt and unpaved roads ($p > 0.05$). Litter and air temperatures did not show significant differences between distances to edge ($p > 0.05$ in all distances) (Table 2).

4.2. Light

Light intensity showed significant reductions between road edge and interior in both laurel and pine forests (Table 1, Fig. 3). Significant light reduction persisted up to 6 m from both road edges in laurel forest, and from asphalt roads in pine forest, whereas it persisted to 1 m in unpaved roads in the pine forest ($p > 0.05$).

Mean (±S.D.) total light intensity at the floor level was significantly higher in the pine forest, 28.5 ± 26.7 klx, than in the laurel forest (20.2 ± 38.5 klx), regardless of distance to the edge (Fig. 3). In the laurel forest, light intensity averaged 63.4 klx (±50.2 S.D.) at the road centre (−3 m) and 9.4 klx (±9.5 S.D.) at forest interior (100 m) for both road types (net average difference between extremes = 54 klx). In the pine forest, light intensity averaged 52.7 (±37.5 S.D.) at the road centre and 15.7 (±9.7 S.D.) at the interior (net average difference = 37 klx). Comparing light intensity between the road centre and the interior, ~96% of total light received in the laurel forest is filtered at the interior (100 m), whereas in the pine forest about 30% of the total light is filtered at 100 m.

4.3. Canopy cover and height

We detected overall highly significant gradients for canopy cover and height in the laurel forest, but not in the pine forest (Table 1, Fig. 4). In the laurel forest, canopy cover stabilized at
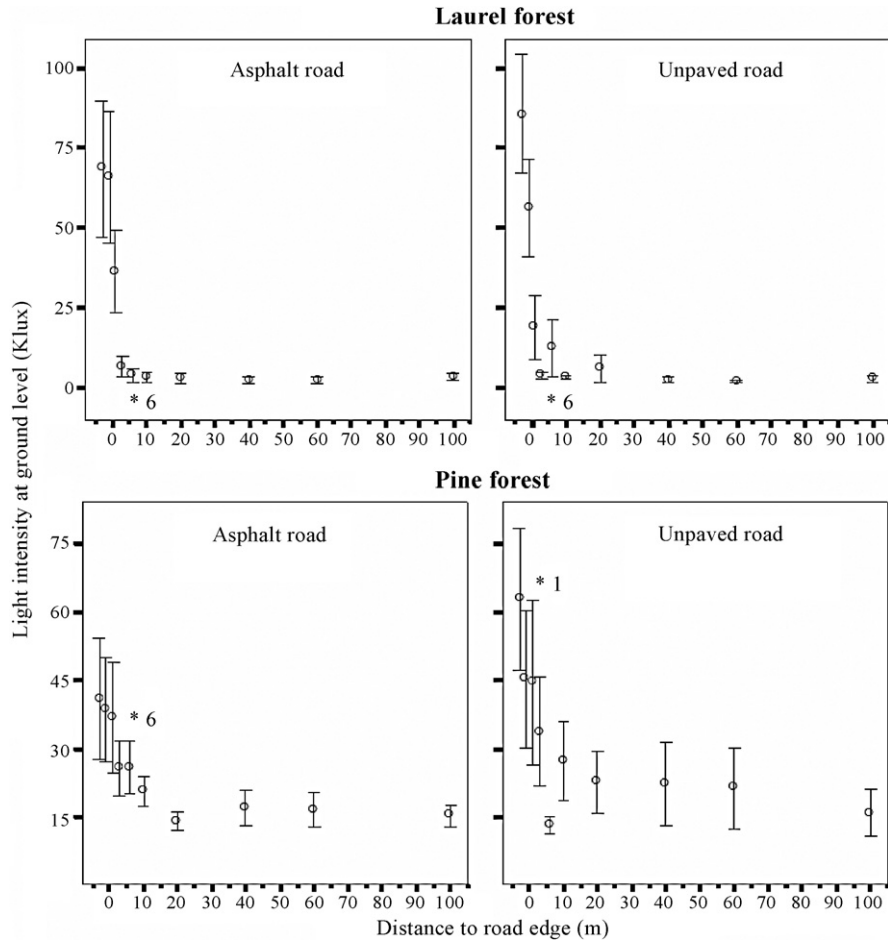
Fig. 3. Variation in light penetration from asphalt roads and dust trails to the interior of laurel and pine forests. Negative distances are on the road right-of-way. Shown are mean ± 1 S.E. (vertical bars). Asterisks denote the distance-to-edge beyond which no significant effect is detected.
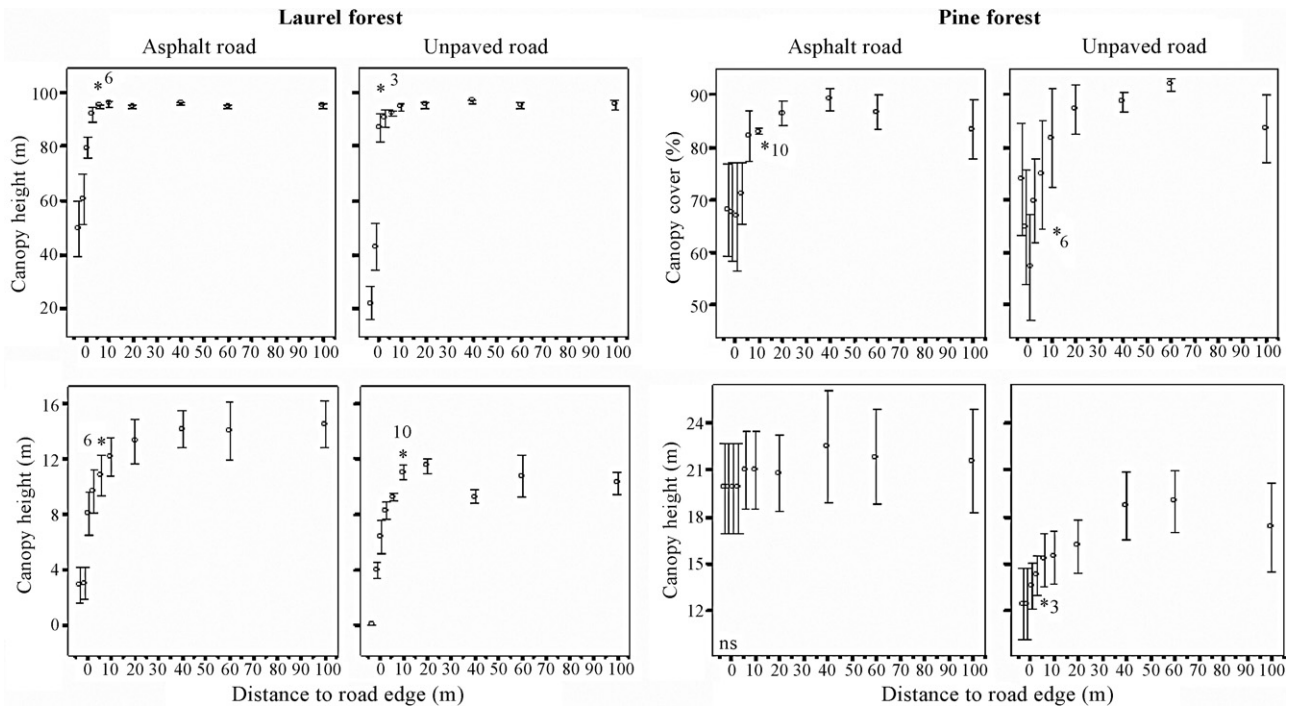

Fig. 4. Variation in canopy cover and height from asphalt roads and dust trails to the interior of laurel and pine forests. Negative distances are on the road right-of-way. Shown are mean ± 1 S.E. (vertical bars). Asterisks denote the distance-to-edge beyond which no significant effect is detected.

Table 2
Results of the Helmert contrasts for the road edge effect

Variable	Distance to road (m)	Temperature (°C)				Light (klx, ground level)	Canopy	
		Soil	Litter[a]	Air (5 cm height)	Air (1.3 m height)		Cover (%)	Height (%)
Laurel forest		Asphalt road						
	−3	–		–	–	–	–	–
	−1	**0.000**		0.070	0.200	**0.000**	**0.000**	**0.000**
	1	**0.000**	–	**0.020**		**0.000**	**0.000**	**0.000**
	3	0.129	**0.014**	0.134		**0.000**	**0.004**	**0.027**
	6		0.287			0.392	0.539	0.139
		Unpaved road						
	−3	–		–	–	–	–	–
	−1	**0.000**		**0.003**	0.055	**0.000**	**0.000**	**0.000**
	1	**0.000**	–	**0.010**		**0.000**	**0.000**	**0.000**
	3	0.146	0.103	0.804		**0.001**	0.092	**0.000**
	6					0.712		**0.045**
	10							0.293
Pine forest		Asphalt road						
	−3	–		–	–	–	–	–
	−1	**0.001**		0.180	0.581	**0.040**	0.082	0.693
	1	**0.000**	–			**0.025**	**0.047**	
	3	0.229	0.081			**0.025**	**0.017**	
	6					0.167	**0.042**	
	10						0.600	
		Unpaved road						
	−3	–		–	–	–	–	–
	−1	0.181		0.679	0.550	**0.003**	0.646	0.050
	1	**0.017**	–			0.053	0.096	**0.029**
	3	0.425	0.454				**0.005**	0.369
	6						0.097	

Distance to road beyond which no significant variation was detected, shown as a change from a significant value (bold) to a not significant value of p (significance level, set at $\alpha = 0.05$) for a given variable. Negative numbers are distances on the road pavement.

[a] Note that for litter temperature, only distances beyond the road edge are considered.

6 m from asphalt roads and at 3 m from unpaved roads ($p > 0.05$). Canopy height stabilized at 6 m from asphalt roads and at 10 m from unpaved roads ($p > 0.05$). In the pine forest, variation in canopy cover stabilized at 10 m from asphalt roads and at 6 m from unpaved roads (Table 2, Fig. 4). Canopy height did not differ significantly on asphalt roads ($p > 0.05$ for all distances), and stabilized at 3 m from unpaved roads.

The tree canopy was almost twice as high and ~25% less dense in the pine forest (height: 17.9 ± 6.4 m; cover: $59.2 \pm 29\%$) than in the laurel forest (height: 9.4 ± 5.3 m; cover: $83.7 \pm 23.1\%$), regardless of distance to road.

4.4. Effect of type of road surface (asphalt versus dust) on road edge effects

The road type (dust trail versus asphalt road) had a significant effect in the edge-to-interior gradient in temperature in both forests (Fig. 2): (a) laurel forest (soil: $F = 11.766$, $p = 0.001$; litter: $F = 37.791$, $p < 0.001$; air at 5 cm: $F = 34.405$, $p < 0.001$; air at 1.3 m: $F = 35.231$, $p < 0.001$); (b) pine forest (soil: $F = 54.654$, $p < 0.001$; litter: $F = 8.225$, $p = 0.005$; air at 5 cm: $F = 10.485$, $p = 0.002$; air at 1.3 m: $F = 14.652$, $p < 0.001$). The laurel forest showed higher average temperature (at the four vertical layers) along unpaved road–interior transects than along asphalt

road–interior transects (Fig. 2). The opposite was detected for the pine forest (Fig. 2). The difference in average temperatures between both corridor types was higher in the pine forest than in the laurel forest (Fig. 2).

The corridor type had no significant effect on the light gradient in the laurel forest ($F = 1.113$, $p = 0.293$) or the pine forest ($F = 0.019$, $p = 0.891$). We detected no significant effect of road type on the gradient in canopy structure in the laurel forest (cover: $F = 0.622$, $p = 0.432$; height: $F = 0.575$, $p = 0.450$) or the pine forest (cover: $F = 1.352$, $p = 0.248$; height: $F = 2.950$, $p = 0.089$) (Fig. 4).

5. Discussion

We have detected short and abrupt gradients from the road edge to the interior of the Canarian laurel and pine forests in temperature, light and canopy traits. Overall variation in temperature, light and canopy showed a general stabilizing trend within the first 10 m from road edges in laurel and pine forests. No microclimatic change seemed to persist after 6 m to the interior of any forest during the study period. Our results suggest that road edge effects defined by temperature, light, and canopy cover and height, may be shallower for our study forest than for other edge types, including some road systems studied on

continental grounds (e.g. Williams-Linera, 1990; Fraver, 1994; Matlack, 1993; Young and Mitchell, 1994; Goosem and Turton, 2000; Dignan and Bren, 2003). Nevertheless, changes in canopy structure caused by natural factors (such as relief, aspect or soil patchiness), or by anthropogenic factors, can modify the patterns of microclimate edge effects revealed here (e.g. Miller et al., 1996; Lugo and Gucinski, 2000).

The patterns reported here could vary in different years, seasons, hours, and under variable wind strength and direction, or between edges of different ages (Matlack, 1993; Turton and Freiburger, 1997; Honnay et al., 2002). For example, microclimate gradients across edges may be extreme on sunny and/or windy days (Forman, 1998). In our study, light penetration was estimated at the center of the day, when sun is nearly perpendicular to the road. Light reaches greater horizontal distances into the forest at morning and afternoon hours, when the sun angle is smaller (Stoutjesdijk and Barkman, 1992). Microclimate edge depths along the same roads for extreme seasonal or daily variation should be compared to reveal different patterns (Saunders et al., 1999; Chen et al., 1996).

For a number of microclimate, composition, aspects, vegetation and edge types, the edge effect has been found to be deeper, shallower and similar to those of our study. There is a wide spectrum of study methods, ecosystem types, orientations and time of day or year for which microclimate edge effects have been measured. In Australian riparian forests, Dignan and Bren (2003) reported light attenuation levels at heights above ground from 1–7 m to change significantly within 13–105 m from edges with different aspects (N, E and W). In recent Amazonian forest fragments, light levels increased to 40 m inwards the fragment core (Kapos, 1989). MacDougall and Kellman (1992) found increased light levels in long-established tropical gallery forest reaching only 10–12 m. Honnay et al. (2002) found, in mixed deciduous forest, that air temperatures increased to 20–23 m from south-facing edges, whereas soil temperatures changed only within the first 3 m. The same authors reported no significant gradients for temperature from north-facing edges. In addition, PAR experienced changes only 0–3 m from both N and S edges (Honnay et al., 2002).

As laurel and pine forests clearly differ in climate and general stand structure and composition, our result of different intensity and reach of edge effects between forests is not surprising. In the pine forest, a sparser canopy, and higher sun radiation and hydric stress (Tausz et al., 1998) may cause lower contrast between road and interior microclimate. In comparison, along some laurel forest roads vegetation is highly concealed, forming a vertical foliage screen that filters road light, heat and wind, protecting the adjacent horizontal surfaces (Tuller, 1973). There is also a steep vertical gradient running from outside the canopy down to the forest floor along which temperature and sunlight is reduced (Aschan et al., 1994), as described for other forests (Stoutjesdijk and Barkman, 1992). In the laurel forest, only 4.2% and 2% of incident global radiation and PAR respectively, reached the forest floor (Aschan et al., 1994). Moreover, the laurel forest is located within or below the cloud layer, which also buffers the local climate (Höllermann, 1981). Such buffering effect is much lower at our pine forest sites, located on S-SE slopes and at

higher elevations on Tenerife. These factors probably contribute to make the transition in abiotic factors and canopy structure between road and interior sharp in the laurel forest, and more diffuse in the less dense pine forest.

The depth of the thermal transition zone between forest gaps and interior can oscillate greatly throughout the day (e.g. 45 m, Saunders et al., 1999; Chen et al., 1993, 1995). The thermal gradients shown here were rather short (1–6 m), but their amplitude between road edge and forest interior might vary by night. The heat accumulated during the day is dissipated from the road surface to the atmosphere as infrared radiation, creating a heat island around the corridor (Bogren and Gustavsson, 1991). Air and surface road temperature, and thus the heat island shape and extent, may vary with topography, orientation and wind (Gustavsson, 1990; Bogren and Gustavsson, 1991). In addition, the type of surface (asphalt versus earth) may be important in determining the depth and temporal variation of road edge effects, perhaps due to the physical traits of the pavement material (e.g. albedo and thermodynamic properties, Gustavsson, 1990). Our study suggests that asphalt roads induce a slightly steeper gradient in temperature than dust trails, as revealed in both laurel and pine forests, especially in the aboveground temperatures. This indicates that, other factors fixed, surface type may play an important role in shaping road-interior gradients in microclimate, and by extension in plant and animal communities.

Although apparently short, the extent of the microclimatic edges described here has some implications for both invasive and native plant species. The depth of the road edge effect for light penetration was 6 m in both forests. Some exotic weeds that are shade-intolerant cannot establish in the light conditions that exist under closed canopy (Parendes and Jones, 2000), whereas others are able to germinate under a closed canopy, maintain a seedling bank and grow (e.g. Clement et al., 1991). At least in our laurel forest sites, up to ~90–95% of the total light is filtered at shaded interior locations, whereas light availability was higher in the pine forest. Höllermann (1981), Aschan et al. (1994), and Gabriel and Bates (2003) obtained similar levels of light extinction through laurel forest canopy. The small depth for the light edge effect found in this study may act as a barrier against the establishment of shade-intolerant invasive species, at least in the laurel forest (Arévalo and Fernández-Palacios, 2000). The high illumination values obtained at the road gap (>100 klx; photosynthetically active radiation [PAR] ~2000 μmol s^{-1} m^{-2}) are far higher than the light compensation and saturation points of photosynthesis required by higher plants and bryophytes adapted to low light levels (Gabriel and Bates, 2003). Global radiation has been found to reach typical forest interior levels within ~2–20 m from the edge, depending on vegetation type and canopy architecture (Kapos et al., 1997; Brothers and Spingarn, 1992; Matlack, 1993; Cadenasso et al., 1997).

Edge orientation controls the penetration of directional influences like wind or sunlight. Equator-facing edges (south-facing edges in the northern Hemisphere, north-facing edges in the southern Hemisphere) experience maximum penetration of light, temperature increase and desiccation (Chen et al., 1995; Burke and Nol, 1998; Forman, 1998; Dignan and Bren, 2003).

In spite of selecting mostly south-facing edges, the depth of road edge effects shown here at the two forests was consistently small, compared to other studies of similar orientations (up to 60–180 m; Forman and Godron, 1986; Young and Mitchell, 1994; Chen et al., 1995; Brosofske et al., 1997; but see Brothers and Spingarn, 1992). The edges studied here would experience a buffering effect of the subtropical latitude of the Canary Islands, compared to those of higher latitudes. This hypothesis is coincident with the fact that difference in light intensity between south and north facing edges increases with distance from the equator (Forman and Godron, 1986).

Our study suggests that interior forest conditions similarly appear after 6–10 m from the road edge in the laurel and the pine forest. Such apparent edge widths may accumulate at the landscape and regional scales to reduce net forest area and species richness (Reed et al., 1996; Findlay and Houlahan, 1997). Within this distance from roads, major changes in the biota and community processes are likely to occur (Watkins et al., 2003). If roadsides suffer higher temperatures and light incidence than interior forest (even with minimal propagation of edge effects), greater fragmentation would lead to increased temperatures and higher light intensities reaching the forest floor at the island scale. Typical laurel and pine forest roads are about 7 m wide. Therefore, the total amount of forest area removed and climatically transformed by a road is 2.7 ha km^{-1} (0.027 km^2) for an edge depth of 10 m along both roadsides (an edge depth comparable to those reported here). A possible consequence of this depth of road edge is that it accumulates across the island area. Among such probable cumulative impacts are the increase in marginal habitat for sun-loving animal species within the forest matrix (e.g. lizards, Delgado et al., in press), predators (e.g. introduced rats, Delgado et al., 2001, 2005), and exotic plants (Arévalo et al., 2005).

Conversely, rare and threatened bird species (like the Canarian-endemic fruit pigeon, *Columba bollii*), with strict forest-interior requirements, might suffer from net habitat loss and road edge effects (Delgado et al., 2005). Fleshy-fruit production is increased along roadsides in the laurel forest, in relation with a higher productivity through higher light availability (Luken et al., 1991). Frugivorous pigeons could be attracted to road edges by increased visual signal from fruit displays and by more predictable and accessible fruit resources in time and space (Nogales et al., 1999; Bach and Kelly, 2004). A generally assumed effect of attraction to road habitat for birds is increased mortality to car collisions (Clevenger et al., 2003) and enhanced predation (Bergin et al., 2000). For instance, higher egg and nest predation has been detected for neotropical birds along rural forest edges (Danielson et al., 1997). However, these issues are still poorly investigated for the Canarian forest roads.

When creating buffers and managing the landscape surrounding roads (e.g. exotic weed control, selective cuts, road closure), we should take into account microclimate edge depths, test for its temporal and spatial variation, and assess its effects on native and exotic biota and community processes, especially on spatially-limited island grounds. This should aid in the design of better road schemes, integrating road management and construction practices into forest conservation.

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