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ORIGINAL PAPER

Vegetation patches improve the establishment of *Salvia mexicana* seedlings by modifying microclimatic conditions

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Abstract Human disturbance has disrupted the dynamics of plant communities. To restore these dynamics, we could take advantage of the microclimatic conditions generated by remaining patches of vegetation and plastic mulch. These microclimatic conditions might have great importance in restoring disturbed lava fields located south of Mexico City, where the rock is exposed and the soil is shallow. We evaluated the effects of both the shade projected by vegetation patches and plastic mulch on the mean monthly soil surface temperature (T_{ss}) and photosynthetic photon flux density (PPFD) and on the survival and growth of *Salvia mexicana* throughout the year. This species was used as a phytometer of microsite quality. Shade reduced the T_{ss} to a greater extent than mulch did. Both survival and growth were enhanced by shade and mulch, and the PPFD was related with seedling growth. During the dry season, plant biomass was lost, and there was a negative effect of PPFD on plant growth. At micro-meteorological scales, the use of shade projected by patches of vegetation and mulch significantly reduced the mortality of *S. mexicana* and enhanced its growth. Survival and growth of this plant depended on the environmental quality of microsites on a small scale, which was determined by the environmental heterogeneity of the patches and the landscape. For plant restoration, microsite quality must be evaluated on small scales, but on a large scale it may be enough to take advantage of landscape shade dynamics and the use of mulch to increase plant survival and growth.

Keywords Edges of vegetation fragments · Facilitation · Reforestation tools · Small meteorological scale · Soil and surface temperature

Introduction

For vegetation recovery during ecological restoration we must learn more about the first steps of the plant life cycle and the microclimatic field conditions that enhance seedling survival and establishment (Meiners et al. 2002). Thus, it is critical to know how to take advantage of the remaining vegetation in disturbed areas to optimize seedling recruitment. Intrinsic attributes of the vegetation edges, such as fragment size, plant density and tree height, determine the daily and seasonal microclimatic conditions in the adjacent areas, creating new environments for other species that do not tolerate matrix conditions (Shachak et al. 2008). One of the main roles of vegetation fragments is to intercept radiation, thus reducing air and soil surface temperature fluctuations and photosynthetic photon flux density (PPFD), and improving

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the retention of soil moisture (Tsuyuzaki et al. 2012), which is critical during the early stages of plant development.

The use of vegetation fragments and isolated trees to facilitate plant re-establishment represents a complementary, scalar approach to restoration ecology. However, little is known about the seasonal variability of microenvironmental conditions near small vegetation fragments (patches) and the relationship between this variability and the responses of the individual plants, such as mortality and growth of key species (Pickett et al. 1989; Peña-Becerril et al. 2005). Additionally, the combined effect of preexisting vegetation patches and using inexpensive agricultural techniques to improve the recovery of vegetation (Feng-Ming et al. 1999) requires further exploration.

Plastic and biodegradable mulches can buffer abiotic stress (Kasirajan and Ngouajio 2012). Plastic mulches play an important role in crop growth because they modify soil temperature and reduce evaporation (Lalitha et al. 2010); they have also been used for weed control (Krishnapillai 2009) and to favor nutrient cycling (Wallace et al. 2012). However, plastic mulches have been used only rarely to induce ecosystem recovery (Riege and Sigurgeirsson 2009).

Considering that the use of fragment edges facilitates the advance of the forest edge toward the adjacent matrix at different scales (Yoshihara et al. 2010), we tested the combined effects of small vegetation patches immersed in a fragmented landscape and white plastic mulch (for vegetable production) on the survival and growth of *Salvia mexicana* seedlings in a disturbed lava field located south of Mexico City. *Salvia mexicana* is a semideciduos shrub (it loses most or only a small part of its biomass in response to stressing conditions) important structural species in gaps and in disturbed temperate forests (Cornejo-Tenorio and Ibarra-Manríquez 2011), similar to the environment of our study area (Gónzalez-Hidalgo et al. 2002). Besides, *Salvia* species facilitate the establishment of *Quercus* spp., in other ecosystems (Gómez-Aparicio et al. 2004; Castro et al. 2006).

In order to increase shrub recruitment in disturbed lava fields, we took an integrative analysis approach using *S. mexicana* as a phytometer species (sensu Kikvidze and Armas 2010). We evaluated how plants take advantage of the microclimatic variability created by small patches of vegetation and the use of plastic mulches at a range of smaller meteorological scales from β (200–20 m), γ (20 m–2 m) and δ (2 m–2 mm). With this purpose in mind, we identified shaded (North North West, NNW) and exposed sites (South, S) around five vegetation patches and compared the effects of these orientations on the soil surface temperature (T_{ss}) and PPFD; and evaluated how these microclimatic variables affect the survival and growth of our phytometer species, *S. mexicana*. We hypothesized that the microclimate created by the combined effects of the shade projected by the patches and of the mulch will affect *S. mexicana* survival and growth depending on the season of the year, the variation in patch size and structure (such as canopy opening, vegetation height and plant density), and the lava substrate.

In this study, we (1) determined the microclimate created by vegetation patches and plastic mulch, (2) compared the effect on the survival and growth of *S. mexicana* seedlings of the microclimate inside (NNW) and outside (S) of the shade projected by vegetation patches; (3) determined the effect of white plastic mulch on the same growth variables; (4) tested the combined effect of these two factors on the survival and growth of *S. mexicana* seedlings; (5) related the light (at the seedling type level) and T_{ss} to growth variables measured in the seedlings; and (6) related patch size and structure to plant survival.

Materials and methods

Study area and seed collection

The study area is located at 2,400–2,850 m a.s.l., inside a protected natural area—Parque Ecológico de la Ciudad de México (PECM, 19°15′32″N, 99°12′1.9″W). In this park, the climate is Cb'(w2)(w) (temperate by elevation, with a long sub-humid fresh summer), the mean annual temperature is 14 °C and the mean annual precipitation is 880 mm, with 80 % of the precipitation occurring between June and October (Fig. 1; Gónzalez-Hidalgo et al. 2002). The PECM surface area is 727 ha, 29 % of which has suffered disturbance by illegal settlements from 1980 to 1989. Inside the park, we selected a lava field (1,650–2,000 years old, Siebe 2000). In this area, the mean thickness of the lava layer is 7 m (1–12 m, Delgado et al. 1998; Lorenzo Vázquez Selem, personal communication); this field was originally covered with xerophilous shrubland and oak forest and is currently undergoing different stages of recovery. *Salvia mexicana* seeds were collected in the PECM from more than ten plants during the dry season (December 2008).

Selection and characterization of the vegetation patches

The five vegetation patches (located between 2,600 and 2,650 m a.s.l.) were selected inside a 25-ha area that is covered by fragmented vegetation that includes small patches of oak forest immersed in a matrix of open secondary xerophilous shrubland. To locate the shaded and exposed areas around the five forested patches, we georeferenced a Google Earth image of the park taken in 2009 (Fig. 1), and we superimposed on it a layer with a topographic map with contours drawn every 10 m. Based on this information and using the software ArcView Gis v.6 (ESRI, New York, NY) and Google SketchUp v.8, we developed a digital landscape model to

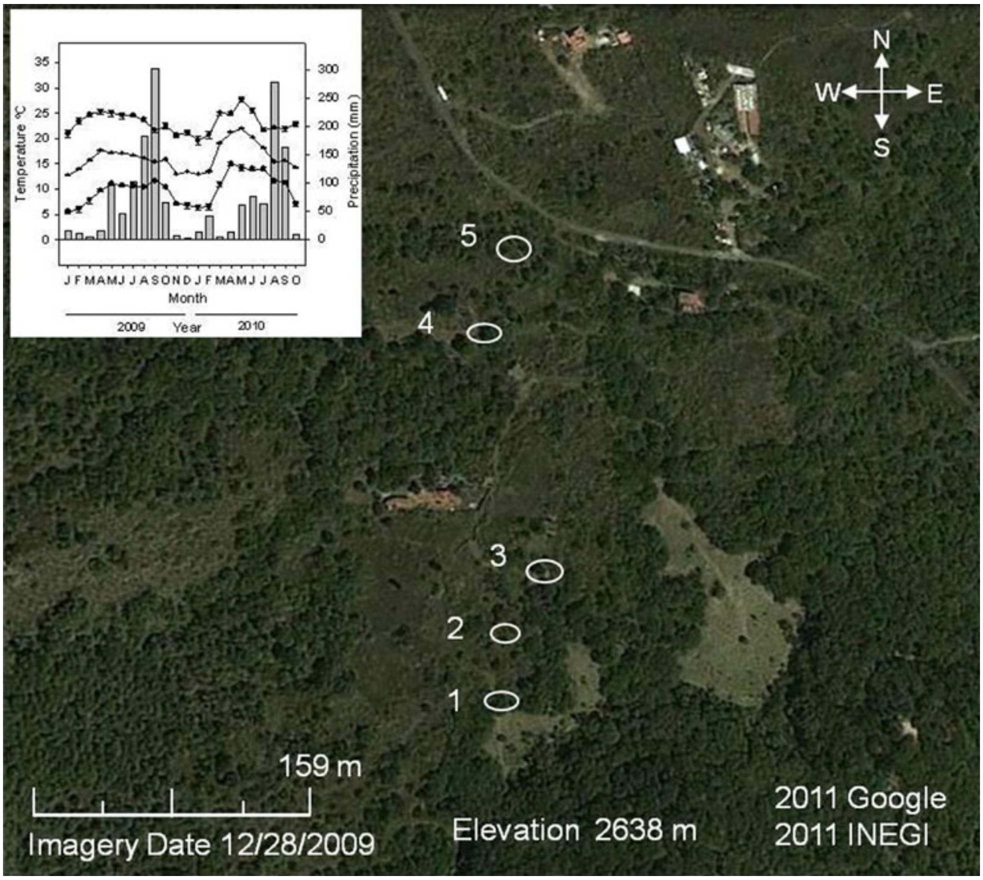


Fig. 1 Aerial view of a 25-ha area of oak forest and xerophilous shrubland that was disturbed by an urban development. The *ovals* indicate schematically the form and size of the small vegetation patches used as shade sources in this work. *Inset upper left* Monthly mean, maximum and minimum temperatures and precipitation during the study period at the Parque Ecológico de la Ciudad de México (PECM). Standard errors are indicated

which we added virtual shrubs and trees with aggregation patterns that were similar to those observed in the Google Earth image. Google maps imagery observations were also verified on the field. Next, we constructed a model of the shade dynamics throughout the year, and for each one of the five vegetation patches, we located the exposed and the shaded areas during the dry season (Fig. 2).

The five patches that were selected cover irregular areas, vary in size, tree density and canopy opening and are similar in slope (3−10°); these and other site traits are shown in Table 1. The identity and the crown cover of each species, growing in each patch were also determined (Table 2). These patches are inside a matrix area where the vegetation was removed and/or the upper volcanic substrate layer was fragmented with machinery to flatten the area. Among the small rock fragments, shallow soil has accumulated, and the vegetation recovery is poor. During the rainy season, the matrix is covered by isolated perennial small trees and shrubs and seasonal vegetation (deciduous grasses, herbs and suffrutex), whereas during the dry season, it is covered only by perennial vegetation and the debris from seasonal vegetation.

Microclimatic characteristics of the areas around the patches

In order to relate the microclimate at small scale with the individual growth of *S. mexicana*, from October 2009 to July 2010 (10 months) in both the shaded and the exposed (control) areas, the PPFD (400–700 nm) and T_{ss} were measured every hour and every 20 min, respectively, from 0800 hours to 1700 hours. The PPFD was measured at the tips of *S. mexicana* seedlings introduced to the PECM, as high as the seedlings grew in height, using two LI 185A

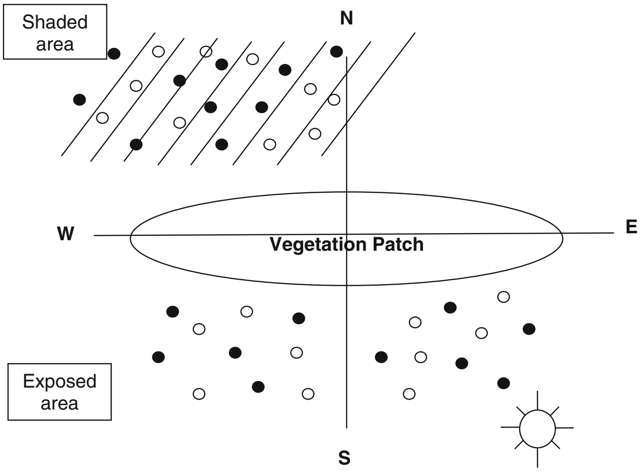


Fig. 2 Diagram of one of the patches where seedlings of *Salvia mexicana* were planted in exposed and shaded areas, located in two orientations with respect to a vegetation patch. The shaded area is represented by *diagonal lines*. *Black circles* Seedlings with mulch, *white circles* without mulch

Table 1 Characteristics of the vegetation patches selected as shade source for *Salvia mexicana* seedlings. T_a Air temperature, *PPFD* Photosynthetic photon flux density. Standard deviations are indicated in parenthesis

Patch traits	Patch				
	1	2	3	4	5
Area (m^2)	329	260	396	350	508
Slope (%)	3–5	10	10	7–10	5
Canopy opening (%)	30	25	20	45	50
Canopy height (m)	9	6	7	7	10
Soil depth (cm)	8	6	6	7	9
Thickness of litter (cm)	4	4	3	5	7
Bare rock substrate (%)	25	35	30	15	10
Herbaceous vegetation (%)	30	35	30	35	25
Shrubby vegetation (%)	45	30	40	50	65
Mean T_a (°C), in exposed sites	26.28 (5.34)	25.77 (4.76)	25.83 (5.85)	26.31 (7.03)	24.19 (5.28)
Mean T_a (°C), in shaded sites	21.22 (5.32)	23.22 (6.46)	21.73 (7.17)	21.19 (6.03)	21.77 (6.15)
Mean PPFD (μmol m^{-2} s^{-1}), in exposed sites	829 (131)	835 (292)	731 (254)	762 (201)	829 (131)
Mean PPFD (μmol m^{-2} s^{-1}), in shaded sites	240 (147)	607 (303)	342 (230)	543 (277)	724 (240)

quantometers (LI-COR, Lincoln, NE) provided with quantum sensors LI-190SA (400–700 nm). The T_{ss} was recorded with 60 dataloggers (HOBO U12-013 Onset Computer Corporation, Pocasset, MA) which accept two thermocouple probes TMC6-HD (interval: from −40 °C to 100 °C, accuracy ±2.5 % of absolute reading) and an internal thermistor (resolution: ± 0.03 °C; accuracy: 0.35). In this case only one thermocouple was placed on the soil surface, close to the bases of the stems of 60 seedlings. To avoid dataloggers overheating, the house holding and the cables were covered by soil and litter brought from an oak forest. From these, six thermocouples were placed

Table 2 Plant cover of each species growing in the five vegetation patches included in this study. All species are part of the understory (plants≤1.5 m), except *Quercus rugosa* and *Buddleja cordata*, which are also part of the canopy. *N* North, *S* South

Patch number	1		2		3		4		5	
	Cover (m^2)									
Species	N	S	N	S	N	S	N	S	N	S
Agave salmiana	0.96			2.07						
Ageratina glabrata	3.64	3.84	6.19	1.50	4.96	2.51	1.66	2.09	10.55	10.81
Garrya laurifolia									2.97	
Arbutus xalapensis					7.85					
Arracacea tolucensis									0.19	
Baccharis conferta		4.49	1.30			5.36		2.59		
Buddleja parviflora						3.02				
Buddleja cordata	98.7[a]		785[a]		118.8[a]		105[a]		152.4[a]	
	14.43		4.48	15.71			1.04		2.10	11.78
Muhlenbergia robusta						1.23				
Stevia micrantha				0.10						
Quercus rugosa	230.7[a]		182[a]		277.2[a]		245[a]		355.6[a]	
					0.38					
Sedum oxypetalum	7.70	5.37	2.08	2.14	0.47	4.79	2.39	0.35		
Senecio precox	2.07		0.28				1.50	2.19		
Stevia salicifolia					3.90			7.84		1.63
Verbesina virgata		0.08							0.55	0.17
Wigandia urens				0.92						

[a] Only the total cover for each patch is indicated for *Q. rugosa* and *B. cordata*

in six plants distributed randomly in each of the shaded and exposed sites in all five patches.

To assess the effect of the white plastic mulch on the temperature in the shaded and exposed sites, additionally, we placed other four dataloggers, each with one thermocouple on the soil surface and other thermocouples beneath the mulch in both the exposed and the shaded sites. To evaluate the effect of the lava substrate on the vertical variation of temperature, in a vertical space similar to that occupied for the *S. mexicana* seedlings (over and beneath the soil surface), at the beginning of the spring, when cold (as in winter) and warm days (as in summer) can occur in the same month, we deployed six additional dataloggers, to characterize the variation of air and soil temperature over full days in three microsites: (1) an exposed area, (2) a patch with an open canopy, and (3) another with a closed canopy. Two dataloggers were distributed evenly in each of the three different locations: the logger housing was buried 5 cm under the soil (T_{-5}), one thermocouple was placed 3 cm above (T_3), and other 45 cm above the soil surface (T_{45}), close to the maximum seedling height recorded. To ensure that the air temperature (T_a) was measured, the thermocouples tips were hanging from stems or branches of shrubs or trees at the indicated vertical locations. In order to calculate the cooling and the heating rates, soil or air temperatures measured on both the warmest and the coldest days in a month (April) were fitted to a logistic dose response peak function (SYSTAT 2002):

$$y[x, a, b, c, d] := a + (4 * b * x\wedge(-d - 1) * c\wedge(d + 1) * d\wedge 2) \\ /(d - 1 + d * x\wedge(-d) * c\wedge d + x\wedge(-d) * c\wedge d)\wedge 2.$$

where y is the temperature as a function of time x, and the following parameters: a=minimum temperature at x=0, a+b= the maximum temperature, c=the time at which the maximum temperature is recorded, d=curve form parameter. In the above equation, x was expressed as a dimensionless variable corresponding to the time expressed in fractions of a 24-h period. The heating and cooling rates were the first maximum and minimum derivatives, respectively, of the curves in each microsite and day, which were analyzed using a two-way ANOVA test.

Seedling propagation, transplantation and evaluation of growth

In order to evaluate the effect of the yearly variation of the shade dynamic on the survival and growth of our phytometer species, we germinated seeds and transplanted to the field seedling of *S. mexicana*. The seeds of this species were sown in Petri dishes and germinated in growth chambers (Lab-Line 455 Instrument, Melrose Park, IL) at 25 °C. Five-day-old seedlings, one seedling per bag, were planted in black plastic bags filled with a mixture of oak forest soil and silica sand (1:1, v:v); 200 seedlings were placed in a shade house and watered every 3rd day at field capacity. After 4 months (in July 2009, rainy season), the seedlings were transplanted to the five selected vegetation patches in the PECM.

In each patch, 40 *S. mexicana* seedlings were transplanted, 20 to shaded sites and 20 to exposed sites. After planting, pieces of white plastic mulch 50×50 cm in size were placed around the base of each half of the transplanted *S. mexicana* seedlings. The factorial design was: 5 patches×2 light exposures (shaded and exposed) × 2 mulching treatments×10 seedlings, for a total of 200 seedlings. The seedling height (from the soil level to the plant tip) and crown cover were recorded for a year and related to T_{ss} and PPFD. To calculate the seedling crown cover, we measured the largest and the smallest diameters and used the ellipse formula.

Data analysis

For each month, the mean daily PPFD and T_{ss} were related with seedling height and crown cover by regression analysis using TableCurve 2D, v3 (AISN Software, Chicago, IL). The patch area, canopy opening and tree density were related to final seedling survival. The patch area, tree density, canopy opening and canopy height were also interrelated. The PPFD and the mean, maximum and minimum T_{ss} were compared among the patches with ANOVA analysis.

Seedling survival as related to light exposure and mulching was analyzed by logistic regression using JMP software (ver. 8.0 SAS Institute, Cary, NC). To determine the effects of light exposure and mulching on seedling height and crown cover throughout the year, we performed repeated measures MANOVAs using JMP software. For these analyses, the patches, as a factor, were included in the model but we did not interpret the results related to these because they were considered replications. For the interactions, P values less than or equal to 0.15 were considered significant because they are more complex than simple hypothesis (Selvin 1996). One MANOVA was performed for each of the growth variables from the exposed sites, and another MANOVA for the data from the shaded sites. Some of the MANOVAs included data only from August 2009 to January 2010 because of the lack of seedlings in all the patches in the remaining months (February–July).

Results

Microclimatic characteristics of the patches

The mean daily T_{ss} value varied significantly throughout the year ($F_{(9,\ 599)}$=145.99, P=0.0001), between light exposures ($F_{(1,\ 599)}$=233.09, P=0.0001) and between patches ($F_{(4,\ 599)}$

=3.63, P=0.006). All of the interactions were significant: time × patch ($F_{(36,\ 599)}$=2.38, P=0.0001), time × light exposure ($F_{(9,\ 599)}$=24.12, P=0.0001), patch × light exposure ($F_{(4,\ 599)}$=5.42, P=0.0003), and time × patch × light exposure ($F_{(36,\ 599)}$=2.89, P=0.0001) (Fig. 3a). The shaded sites had a mean daily T_{ss} value (21.8±6.3 °C) lower than that of the exposed sites (25.7±5.7 °C). The lowest mean T_{ss} was registered in January (16.9±2.7 °C), and the highest ones were observed in May (31.8±3.5 °C). The patch with the lowest mean T_{ss} was patch 5 (23±5.8 °C), and the highest means were recorded in patches 2 and 5 (24.5±5.8 and 23.8 ±6.8 °C, respectively) (Fig. 3a). In the shaded sites, the mean daily T_{ss} value was reduced by the mulch by 0.28± 0.02 °C compared to T_{ss} in sites uncovered by mulch (19.62 ±3.60 and 19.33±3.62 for microsites uncovered and covered by mulch, respectively), whereas the reduction was 1.8 ±0.72 °C in the exposed areas (27.06±8.04 and 25.23±7.31 for sites uncovered and covered by mulch, respectively).

The heating rates were faster than the cooling rates. On the cold day, the site, ($F_{(2,\ 26)}$=29939723. 3, P=0.0001), the position of the sensor with respect to the soil surface (T_{-5}, T_3 and T_{45}; $F_{(2,\ 26)}$=34505211.1, P=0.0001) and their interaction were significant ($F_{(4,\ 26)}$=43777552.7, P=0.0001). The heating rates were faster in exposed sites and slower in shaded sites. In general, heating rates at T_{-5} were significantly slower. In the exposed site, T_{45} had the highest rate (Appendix 1). In the warm day, only the site had significant effect ($F_{(2,\ 26)}$=6.5, P=0.008). In the exposed sites, the heating rates were highest. There were no significant differences in the cooling rates. The highest value in the sum of cumulative temperatures was found in the exposed site at T_{-5}. Conversely, this value was lowest at T_{45} above the soil surface (Fig. 4; Appendix 1). In the exposed site at T_{-5} the cumulative temperatures were the highest of all the microsites (Fig. 4; Appendix 1).

The mean PPFD varied significantly throughout the year (Fig. 3b, $F_{(9,\ 999)}$=332.41, P=0.0001), between the exposed and shaded sites ($F_{(1,\ 999)}$=2039.83, P=0.0001) and between the patches ($F_{(4,\ 999)}$=238.22, P=0.0001). All interactions were significant: time × patch ($F_{(36,\ 999)}$=17.58, P= 0.0001), time × shade ($F_{(9,\ 999)}$=49.30, P=0.0001), patch × shade ($F_{(4,\ 999)}$=136.36, P=0.0001), and time × patch × shade ($F_{(36,\ 999)}$=8.43, P=0.0001). In the exposed sites, the mean PPFD was 789±239 µmol m^{-2} s^{-1}, whereas it was 491± 301 µmol m^{-2} s^{-1} in the shaded sites. The highest mean PPFDs were registered in March (870±269 µmol m^{-2} s^{-1}) and April (888±286 µmol m^{-2} s^{-1}), and the lowest mean occurred in January (319±201 µmol m^{-2} s^{-1}). The lowest mean PPFDs occurred in patches 1 (514±349 µmol m^{-2} s^{-1}) and 3 (537±310 µmol m^{-2} s^{-1}), and the highest mean was registered in patch 5 (776±200 µmol m^{-2} s^{-1}) (Fig. 3b).

Seedling survival

The time, patch and light exposure had significant effects on *S. mexicana* survival (X^2=172.76, X^2=52.61 and X^2=46.72; in all cases P=0.0001; Fig. 5). Mulching exerted a significant effect only when it was interacting with any of the other three factors (time, patch and light exposure). At the end of the observation year, the final survival was 52 % in the mulched microsites compared to 38 % without mulch (X^2=6.67, P= 0.01). After a year, the total survival in the shaded sites was 62 %, whereas it was 30 % in the exposed sites (X^2=15.11, P= 0.0001). Survival varied between 38 % and 66 % for patches 2 and 3, respectively. Survival was highest in patches 3 and 4 (from 40 to 80 and from 60 to 80, for the exposed and shaded sites, respectively). In all of the five exposed and shaded sites, with or without mulch, survival decreased significantly from February to May (X^2=16.00, P=0.003). The decrease in survival was sharpest from March to May. Only in patch 5 was the survival higher without mulch, which was caused by survival in the shaded sites. Only the openings in the patch canopy and seedling survival in the shaded areas had a positive significant relationship with survival (R^2=0.85, P=0.026).

Seedling growth

In the exposed sites of patches 1, 2 and 4, the survival percentages were insufficient for analysis starting in February 2010. Therefore, the effect of light exposure was not analyzed in the subsequent months.

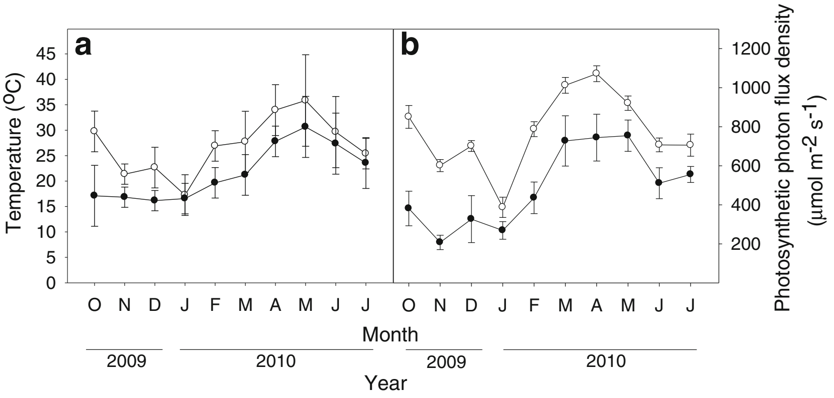
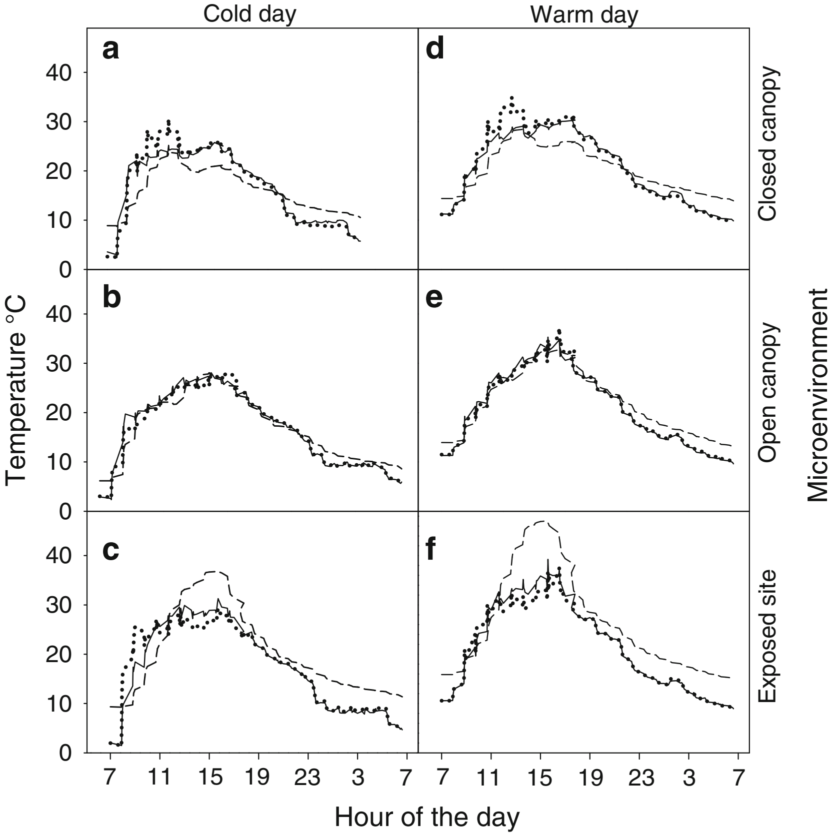


Fig. 3 Mean monthly values of **a** soil surface temperature (T_{ss}) and **b** mean photosynthetic photon flux density (PPFD) in exposed (*white circles*) and shaded (*black circles*) areas near five vegetation patches. *Bars* Standard deviation

Fig. 4 Daily course of mean soil and air temperatures at three vertical locations in relation to the soil surface: buried in the soil at −5 cm in depth (T_{-5}) (*dashed lines*), air temperature 3 (T_3) (*solid lines*) and 45 cm over the soil surface (T_{45}) (*dotted lines*), on 2 contrasting days, in three microenvironments (beneath a closed canopy, an open canopy and an exposed site) of PECM



Seedling height

From August 2009 to January 2010, there was a significant effect for time and for the interaction between time and light exposure; the favorable effect of mulching on seedling height did not change over time (Fig. 6, Appendix 2). There were also significant effects on seedling height related to light exposure and mulching; the interaction between these factors was significant. Without mulching, the seedlings were significantly shorter than with mulching in the exposed sites (Fig. 6a–d).

Within the exposed sites, time of year significantly affected seedling height. In general, plant height increased significantly from August to October and decreased significantly in January 2010, at the beginning of the dry season (Fig. 6a–e). The favorable effect of mulching on seedling height was maintained over time, producing significantly taller seedlings (Fig. 6a–d). Within the shaded sites, the time significantly affected seedling height (Fig. 6f–j). Seedlings were taller from October 2009 to January 2010 and shorter from March to May (dry season); the tallest seedlings in the study year occurred in July.

Seedling crown cover

From August 2009 to January 2010, crown cover followed a similar trend to seedling height throughout the year (data not shown); there were significant effects of time, the interaction between light exposure and time, and finally of light exposure itself (Appendix 2). Crown cover was significantly smallest in January 2010 and greatest from September to November 2009. In August and in the shaded sites, crown cover was larger than in the exposed sites.

In the exposed sites from August 2009 to January 2010, the time and the interaction time and mulching affected the growth of crown cover significantly. Seedling crown cover was significantly the largest in September and subsequently decreased; the smallest crown cover occurred in January. From August to December 2010, mulching had a favorable effect on plant cover. In the shaded sites from August 2009 to July 2010, the time significantly affected the growth of the seedling crown cover. Crown cover was significantly greater from September to December and largest in July. Crown cover was smallest from March to June.

Relationship between mean PPFD and *S. mexicana* seedling growth

The seedling height and crown cover were negatively related (R^2=0.49−0.81, P=0.0001) with the PPFD in October 2009 and January–July 2010. February 2010 (Fig. 7a, b) had a low R^2 (0.54) and July 2010

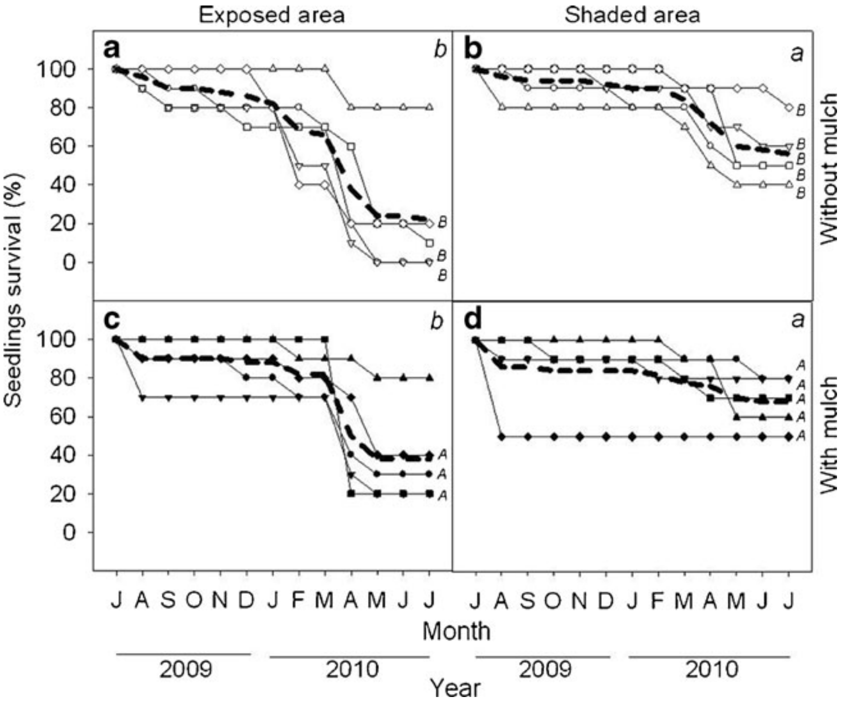


Fig. 5 Survival of seedlings of *Salvia mexicana* planted in exposed (**a**, **c**) and shaded (**b**, **d**) sites close to five vegetation patches in microsites covered (*black circles*) and uncovered (*white circles*) by white plastic mulch. Different *italicised capital letters* indicate significant differences between the mulching treatments, and different *italicised lowercase letters* indicate significant differences between the exposed and shaded sites at the end of the year of study at α= 0.05. *Circles* Patch 1, *squares* patch 2, *up-facing triangles* patch 3, *down-facing triangles* patch 4, *diamonds* patch 5. *Dashed line* Mean survival

(Fig. 7e, f) had a high R^2 (0.72). Overall, seedling height and crown cover decreased significantly as the PPFD increased. In November–December, we found no significant relationships.

Relationship between T_{ss} and *S. mexicana* seedling growth

A relationship between T_{ss} and seedling growth was found mostly in the dry season (R^2=0.17−0.75, $P \leq 0.01$, Appendix 3). For the exposed sites, plant height was related principally to the mean daily amplitude of the T_{ss}; this relationship was significant in January (R^2=0.43, $P \leq 0.01$) and May (R^2=0.67, $P \leq 0.01$). In contrast, plant cover was related more to the mean T_{ss} than to the extreme values or the temperature amplitude. This relationship was observed from November to February (R^2=0.47−0.67, $P \leq 0.01$). In the shaded sites, the growth variables studied were related frequently to the mean T_{ss} variation through time (R^2=0.17 −0.47, $P \leq 0.01$). Plant height was related positively to the daily amplitude of the T_{ss} from November to July (R^2=0.28 −0.69, $P \leq 0.01$), with the exception of March, April and June. In November, this relationship was negative. The relationship of the mean daily T_{ss} with the seedling crown cover did not show a clear pattern over the year; only the minimum T_{ss} affected this variable positively from February to April (R^2=0.49−0.61, $P \leq 0.01$); the same pattern occurred with plant height (R^2=0.21−0.69, $P \leq 0.01$). The relationships of seedling height and crown cover with the mean daily T_{ss} in February and July are shown in Fig. 7c, d, g, h, respectively.

Discussion

In the study area, the characteristics of the volcanic substrate, light exposure and the consequent variations in T_a and T_{ss} affected plant survival and growth. The shade projected by the remnant vegetation patches and the combined use of plastic mulch increased the survival of *S. mexicana* seedlings; both effects reduced the daily fluctuations in the microclimate that surrounds the seedlings, in contrast with the harsh conditions in the exposed areas. However, at small scales (within areas close to vegetation patches), the buffer effect was heterogeneous and dynamic in space and time. The shade projected by the vegetation patches acted at microscales $\beta-\delta$ (200–0.002 m), whereas the mulch and T_{ss} had effects at microscale δ (2–0.002 m; Stull 1988; Orozco-Segovia and Sánchez-Coronado 2009).

Our data showed that the patch shade reduced the mean daily T_{ss} 4 °C in respect to the exposed side, whereas mulch reduced it in a lowest degree (0.28 and 1.8 °C for the shaded and exposed sites, respectively). The reduced effect of the mulch was likely due to the scant soil accumulation on the upwelling dark lava rock. Despite these results, it is known that, in general, mulches reduce heat transfer from the surface to the soil, with a consequent increase in soil moisture (Lalitha et al. 2010). Nevertheless, in the study area and

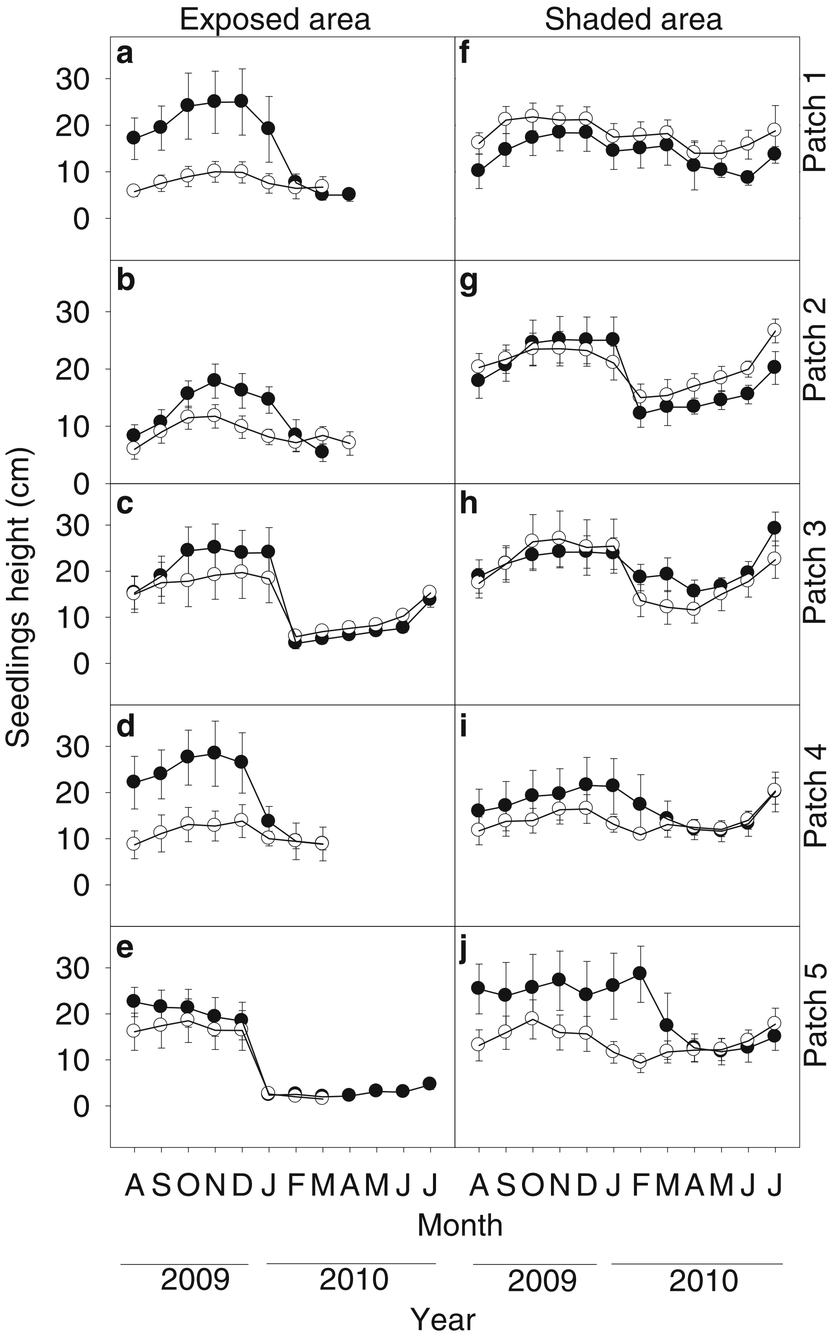


Fig. 6 Mean seedling height of *S. mexicana* planted in exposed (**a**–**e**) and shaded (**f**–**j**) sites close to five vegetation patches and in microsites covered (*closed symbols*) and uncovered (*open symbols*) by white plastic mulch. *Bars* Standard deviation

in the dry season, some data suggest that, in exposed sites, the mulch has no significant effect on soil moisture content (1.67±4.8 % and 3.57±5.9 %, outside and under the mulching, respectively). In contrast, shade favors significantly moisture retention; in the shaded areas the soil moisture is 25.58±2.94 % outside of the mulching and 15.60± 5.67 % under it; soil moisture can even be highest without the mulch because of condensation of moisture on the soil surface early in the morning (A. Orozco-Segovia, personal observations).

The vertical variation in temperature in the gradient studied (from T_{-5} to T_{45}) showed that in the exposed sites at 1510 hours, T_{-5} was 49 °C; while T_3 was 45 °C. This indicates the high capacity for heat storage of the lava rock. In contrast, within the vegetation patches T_{-5} and T_3 were 23 °C and 29 °C, respectively (Fig. 4). In the exposed areas,

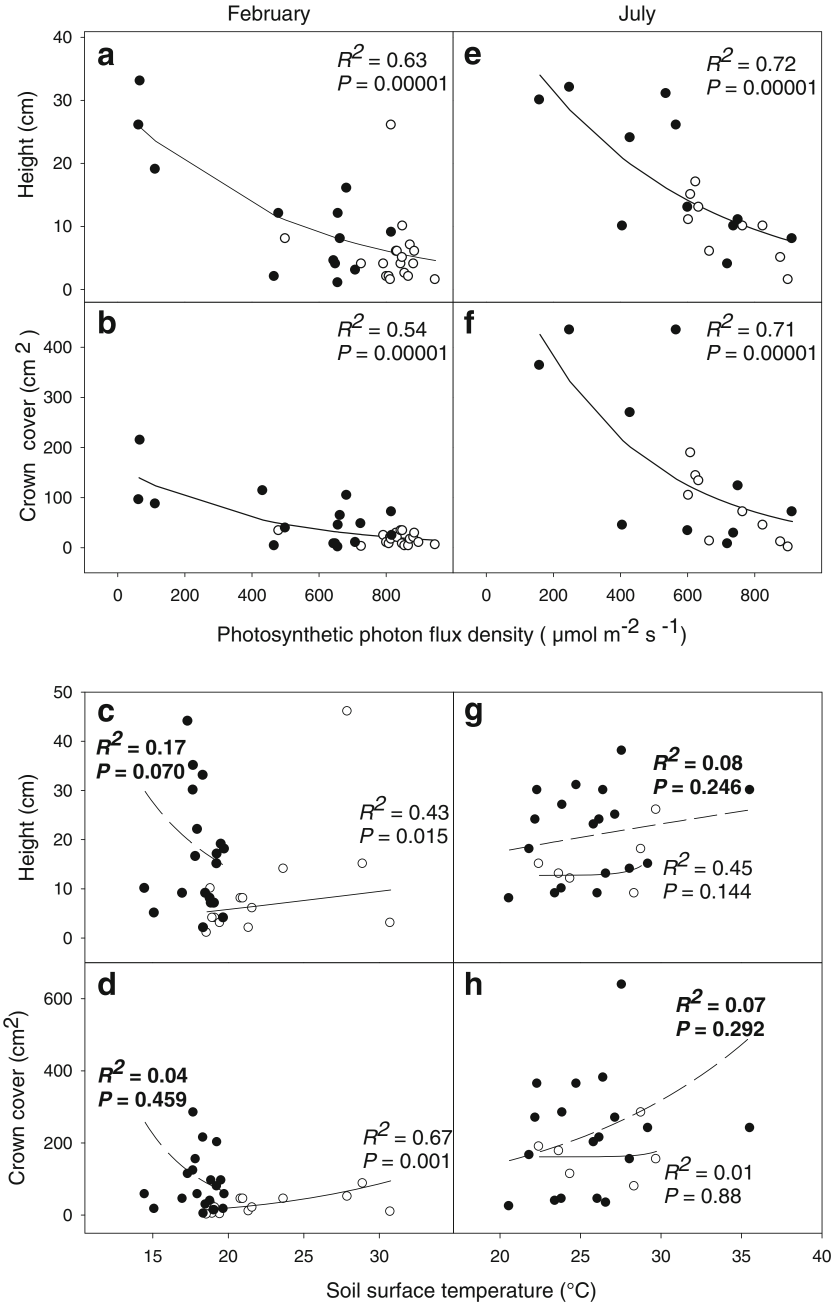


Fig. 7 Relationships between mean daily values of PPFD (in a spring month, February) and (a summer month, July) and (**a**, **e**) the height, and (**b**, **f**) crown cover of seedlings of *S. mexicana*. Months are indicated at the top of the figure. Relationships between mean values of soil surface temperature and (**c**, **g**) height, and (**d**, **h**) crown cover of the seedlings planted in exposed (*white circles*) and shaded (*black circles*) areas during the dry (**a**–**d**) and rainy seasons (**e**–**h**) of 2010. The coefficient of determination and the significance of the regression analysis are shown

the amplitude of the variation in T_{45} (at the highest height reached by the *Salvia* seedlings) was ~27 °C (from 1 °C to 28 °C and from 9 to 37 °C, for cold and warm days, respectively). This variation also occurred in T_{-5} (from 9 °C to 37 °C and from 15 °C to 47 °C, for cold and warm days, respectively), but on warm days the amplitude was greater (~32 °C). The lava rock surface absorbs heat and subsequently radiates this heat back to the surroundings; this might explain the high temperatures registered in T_{45} even under the patch canopy (Short 2005). The high soil and air temperatures observed in the study area, combined with their effect on the evaporation of water in the soil and the added water percolation through cracks in the lava, represent the main constraints for seedling growth and survival, as these directly affect photosynthesis and root growth (Larcher 2003). For example, in *Buddleja cordata*, *Dodonaea viscosa* and *Senecio praecox*, growing in the study area, stomatal conductance drops at T_a close to 28 °C (Barradas et al. 2004).

Throughout the year (Fig. 6), the low but significant relationships found between T_{ss} and the evaluated growth variables suggest that in autumn and winter (dry season), in shaded sites, the temperature affects the seedling height and cover more than in the exposed sites, where T_{ss} was more related to seedling crown cover than to plant height and few significant relationships with temperature were found (Appendix 3). The daily amplitude in the T_{ss} affected height growth more in the shaded sites than in the exposed sites. The lack of a pattern in the distribution of positive and negative relationships between T_{ss} and seedling growth throughout the year reflects the complexity of heat fluxes and other abiotic and biotic factors. These results require additional careful study, not least because the rocky substrate complicates the relationships between substrate traits (soil water potential, water soil evaporation, percolation of water throughout the rock and nutrient cycling, among others) and heat storage and heat flux (horizontal and vertical transfer) throughout the day and year.

The PPFD was reduced by the shade projected by the patches from 789±239 to 491±301 μmol m^{-2} s^{-1}. Photon flux densities in this range are sufficient for optimal photosynthesis in C_3 plants and also for the inhibition of photosynthesis (Taiz and Zeiger 2006). This inhibition by itself may explain why, in several months, we found a negative relationship between crown cover and plant height and the mean PPFD. However, the fact that *S. mexicana* loses part of its foliage in response to water stress at any time of the year, as a strategy to endure the stressful months of the year, explains the biomass reduction. The wide variation in PPFD in the exposed and shaded sites suggests that the quality of planting microsites also varies depending on the path of the sun. During the dry season, several species in the PECM are deciduous, which allows more light to pass through the patch of vegetation and reach certain microsites.

Our results show that the shade projected by plant patches and mulch creates safe sites for seedling establishment. Thus, these are inexpensive restoration tools that may help to reintroduce late successional species in fragmented and altered plant communities. The survival and growth of *S. mexicana* also depended on the microsite quality, which was determined by the environmental heterogeneity in the area, which varied at small scales. The microsite quality might also be modified by other landscape elements, such as neighboring patches or isolated trees and rock and soil distribution, which is a reflection of the high microenvironmental heterogeneity in the PECM. The linear positive significant relationship between openings in the patch canopy and seedling survival in the shaded areas (without mulch) indicates that the shade quality projected by each patch is important. In this study, canopy opening was the only patch trait (as opposed to patch size, plant height or density) that was related to survival, reflecting a variation in the individual tree canopies among the patches or in the tree distribution inside each patch.

Although the results can be related more closely to the mean PPFD and temperature than to mulching, in the exposed areas the seedlings survived in low percentages with mulch, whereas survival was practically zero without mulch, except for patches 3 and 5, where survival was relatively high. In plantings located in wide-open areas of tropical deciduous forests, mulch has been found to have a dominant effect on enhancing survival (Barajas-Guzmán et al. 2006). However, in the heterogeneous landscape of the studied area, and in areas next to the vegetation edge, the effect of mulch was significant but no more relevant than that of the PPFD.

In addition to the simple effect of shade projected by the patches of vegetation, variations in survival and growth might be explained by (1) changes in the orientation of the shade projected due to the rotation of the Earth; (2) the quality of the shade projected for each patch; (3) the projection of the shade of isolated trees and other vegetation patches close to several of the exposed and shaded areas; (4) the phenological changes (leaf drop) in the vegetation; (5) the effect of mulching, either in isolation or in addition to PPFD amelioration by the previous causes, and finally (6) the effect of the distribution of bare rock and the shallow soil on soil and air temperature. The use of shade projected by the patches and mulching reduced the risk of death of *S. mexicana* seedlings and enhances their growth at both the β and the γ meteorological scales. Thus, to enhance the establishment of late successional species, landscape attributes and dynamics must be taken into account.

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Appendix 1

Table 3 First derivatives for the fittings carried out on the daily course of temperature in cold and warm days in three microenvironments in the PECM. First derivative maximum indicates the heating rate and the first derivative minimum indicates the cooling rate. The sum of the cumulative temperature along the day is also shown. Letters indicate significant differences

Site	Cold day					Warm day				
	X value	First derivative (minimum)	X value	First derivative (maximum)	Cumulative temperature	X value	First derivative (minimum)	X value	First derivative (maximum)	Cumulative temperature
Exposed −5 cm	10.66	−3.61 a	4.61	6.28 f	2,965.04	10.27	−4.95 a	4.99	8.00 ab	3,804.45
Exposed 3 cm	12.64	−2.72 a	2.45	6.47 e	2,441.32	12.02	−1.90 a	3.71	4.01 ab	3,169.81
Exposed 45 cm	11.63	−1.74 a	0.00	17,710.70 a	2,326.74	11.70	−1.26 a	2.70	3.09 a	2,929.29
Open canopy −5 cm	12.20	−1.66 a	2.16	4.57 f	2,532.08	12.81	−2.80 a	3.01	5.31 ab	3,141.06
Open canopy 3 cm	12.30	−1.70 a	0.00	81.86 d	2,435.08	11.77	−2.03 a	2.20	5.46 ab	3,053.12
Open canopy 45 cm	12.46	−1.71 a	0.35	6.64 f	2,441.01	12.28	−1.62 a	0.00	7.19 ab	2,982.87
Closed canopy −5 cm	12.21	−1.06 a	1.59	3.27 f	2,537.37	11.57	−2.07 a	0.72	7.50 b	3,086.89
Closed canopy 3 cm	12.69	−1.47 a	0.00	4,760.86 b	2,407.86	11.83	−2.06 a	2.72	5.07 a	3,048.73
Closed canopy 45 cm	11.90	−1.76 a	0.00	968.14 c	2,474.15	11.54	−1.91 a	0.55	7.15 ab	3,054.63

Appendix 2

Table 4 Results of the repeated measures MANOVA's carried out to test the effect of time, light exposure (shaded or exposed) and the presence or absent of plastic mulch, on seedling height and seedling crown cover growth from August 2009 to January 2010 around five vegetation patches. *DF* Degrees of freedom, $\alpha \leq 0.05$ for the main effects and $\alpha \leq 0.15$ for the interactions (according to Selvin 1996)

Source of variation	F	DF	*P*
Seedling height			
Wilk's Lambda=0.63, DF=35, 725.97, *P*=0.0001, for the exposed and shaded areas			
Time	18.89	5, 172	0.0001
Time×light exposure	3.40	5, 172	0.005
Time×mulch	0.99	5, 172	0.42
Patch	2.00	4, 176	0.09
Light exposure	4.13	1, 176	0.04
Mulch	8.36	1, 176	0.004
Light exposure×mulch	3.16	1, 176	0.07
Wilk's Lambda=0.52, DF=25, 306.12, *P*=0.0004, for the exposed areas			
Time	11.88	5, 82	0.0001
Time×mulch	1.03	5, 82	0.40
Patch	1.77	4, 86	0.14
Mulch	11.92	1, 86	0.0009
Wilk's Lambda=0.35, DF=55, 355.37, *P*=0.0045, for the shaded areas			
Time	21.76	11, 76	0.0001
Time×mulch	1.7	11, 76	0.089
Patch	1.66	4, 86	0.16
Mulch	0.32	1, 86	0.57
Seedling crown growth			
January 2010 Wilk's Lambda=0.61, DF=35, 713.35, *P*=0.0001, for the exposed and shaded areas			
Time	29.48	5, 169	0.0001

Table 4 (continued)

Source of variation	F	DF	*P*
Time × light exposure	9.11	5, 169	0.0001
Time × mulch	1.51	5, 169	0.18
Patch	3.01	4, 173	0.019
Light exposure	53.53	1, 173	0.0001
Mulch	0.50	1, 173	0.48
Light exposure × mulch	1.15	1, 173	0.28
Wilk's Lambda=0.66, DF=25, 302.4, *P*=0.09, for the exposed areas			
Time	13.77	5, 81	0.0001
Time × mulch	2.06	5, 81	0.07
Patch	4.71	4, 85	0.0017
Mulch	4.69	1, 85	0.03
Wilk's Lambda=0.35, DF=55, 355.37, *P*=0.004, for the shaded areas			
Time	23.26	11, 76	0.0001
Time × mulch	1.06	11, 76	0.40
Patch	1.72	4, 86	0.15
Mulch	0.36	1, 86	0.54

Appendix 3

Table 5 Significant ($P \leq 0.001$) relationships between the growth parameters (height and crown cover) and the extremes temperatures and the amplitude of the soil surface temperature (T_{ss})

Sites	T_{ss}	Month										
		Growth parameter	O	N	D	J	F	M	A	M	J	J
Exposed	Mean	Height						+[a]				
		Crown cover		+		+	+					
	Maximum	Height	+									
		Crown cover		−		−	−					
	Minimum	Height		+		+						
		Crown cover		+	+							
	Amplitude	Height				+				+		
		Crown cover		+			−					
Shaded	Mean	Height		+	+	+						
		Crown cover		−		+		+				
	Maximum	Height			+	+	+					
		Crown cover										
	Minimum	Height					+	+	+			
		Crown cover					+	+	+			
	Amplitude	Height		−	+	+	+			+		+
		Crown cover		−		+	−					

[a] (+) positive or (−) negative relationship

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