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ORIGINAL PAPER

Soil water, nutrient availability and sapling survival under organic and polyethylene mulch in a seasonally dry tropical forest

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Abstract We examine the effect of mulches on the soil volumetric water content (SVWC), pH, carbon (C), total and mineral (NH_4 and NO_3) nitrogen (N), total and bicarbonate phosphorus (P), and on the survival and relative growth rate of three species, *Ipomea wolcottiana* Rose, *Lonchocarpus eriocarinalis* Micheli and *Caesalpinia eriostachys* Benth, in a degraded seasonally dry tropical forest (SDTF) area. Our study year was unusually dry, with only half of the mean annual rainfall. Sixteen plots (5 × 6 m) for each of our four treatments, mulches with alfalfa (*Medicago sativa* L.) straw, forest litter (SDTF litter), polyethylene and bare soil (control), were used. In each plot, 20 tree saplings were planted of each species. The SVWC was higher in plots mulched with polyethylene than in bare soil plots. The soil pH did not change with mulching, and there were no differences between treatments in the concentrations of soil organic C, total N, NO_3 and total P. However, soil concentrations of NH_4 were highest in plots with alfalfa straw and of bicarbonate P in plots with polyethylene. Sapling survival was higher in polyethylene mulch plots than in other mulching treatments, in the order *I. wolcottiana* > *C. eriostachys* > *L. eriocarinalis*. Sapling survival under organic mulches, alfalfa straw and forest litter were similar, and lowest in bare soil. The relative growth rate followed the order *L. eriocarinalis* < *C. eriostachys* < *I. wolcottiana*, and the growth rate of all species was greatest under polyethylene mulch. We conclude that a combination of polyethylene mulch with species of high growth rate is best for restoring seasonally dry tropical areas.

Keywords *Caesalpinia eriostachys* · *Ipomea wolcottiana* · *Lonchocarpus eriocarinalis* · Low precipitation · Mexico · Restoration

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Introduction

Two main functions of soil are to provide a beneficial environment for plant development and to regulate water flow in the ecosystem. Physical, chemical, biological and mineralogical characteristics of soil have a direct effect on these functions. Soil characteristics have been drastically modified by changes in land use (for example, fertility has been reduced, depth has been modified and erosion loss has increased), especially in developing countries (Etchevers et al. 2000).

In many tropical arid and semi-arid areas a major cause of soil degradation is deforestation for pasture expansion (Maass 1995). Seasonally dry tropical forests (SDTF) are the predominant type of vegetation in these areas; the diversity of life forms in these ecosystems is likely to be associated with water and nutrient availability (Medina 1995). Certainly seasonality in water and nutrient availability plays a major role in the functioning of these ecosystems (Campo et al. 2001a).

Slash-and-burn is the most extensive human land-use in SDTF areas, and it leads to changes in the soil nutrient content (Kauffman et al. 2003). In the short term the soil N and P concentration generally increases in the upper soil; long term, however, the concentration of both nutrients decreases (Ellingson et al. 2000; Giardina et al. 2000; Ketterings et al. 2002). Reductions in soil nutrient and low precipitation may limit the opportunities for forest regeneration in SDTF (Ceccon et al. 2003; Ellingson et al. 2000).

Concern over the reforestation of seasonally dry tropical areas has focused attention on the use of mulches (Grantz et al. 1998; Yohannes 1999). Use of mulches in perturbed areas protects the soil and reduces water and nutrient losses (Paris et al. 1998; Rathore 1998; Shock et al. 1997). On the other hand, the mulches increase both the decomposition rate and the nutrient concentration in the soil (Cogle et al. 1997; Yohannes 1999). In view of the key role of water availability in seasonally dry tropical environments, consideration of mulches has mainly been concerned with plant responses to water (Grantz et al. 1998; Yohannes 1999); the effects of mulching on nutrient dynamics in the soil have scarcely been considered. In this study, we investigated the effects of mulching on saplings of SDTF trees and on soil water availability and nutrients in a perturbed SDTF area of the Pacific coast of Mexico. Our aim was to determine the effects of different mulches (polyethylene, alfalfa straw, and litter of a mature SDTF) on: (1) sapling survival and growth, (2) soil water content, and (3) the carbon (C), nitrogen (N) and phosphorus (P) concentrations in the soil. We expect significant effects of mulching on soil and plant survival, and that the type of mulch is significant. These results should assist in the restoration of seasonally dry tropical forests.

Materials and methods

Site description

The study was carried out in the village of San Mateo, on the Pacific coast of Mexico in the state of Jalisco (19°34′ N, 105°04′ W), in a lowland cattle raising area where SDTF was the original vegetation and was removed approximately 15-year ago. The area had previously been used for maize plantations, as is common in these seasonally dry areas. The landscape of this area is presently covered by *Acacia farnesiana* (L.) Wild (500 ind per ha) and some *Caesalpinia eriostachys* Benth (1 ind per ha), with plants of the Asteraceae family dominating the herbaceous stratus.

The climate in the region is characterized by a seasonal rainfall pattern, with a rainy season (June–October) that provides 90% of the total annual rainfall (mean annual rainfall average 740 mm; García-Oliva et al. 1991). Monthly air temperatures are in the range 22–27°C, with a diurnal variation of 9°C in summer and 14°C in winter (De Ita-Martínez and Barradas 1986). During the study year the cumulative precipitation was 391.6 mm (i.e., approximately 50% of the long-term mean annual rainfall), and the annual average temperature minimum was 17.2°C and the maximum 28.8°C.

The landscape in the area is characterized by convex hillside located 80 m asl facing south; its slope ranges from 5 to 25°. The soil (Haplic Ustarents) is shallow (generally less than 0.6 m in depth), fine and kaolinitic; the parent material is rhyolitic volcanic rock (Campo et al. 2001b). The proportions of clay, silt, and sand in the soil to a depth of 10 cm were respectively 25 ± 3, 24 ± 3, and 51 ± 3% (mean ± 1 SE). The mean P input by bulk deposition and output during a 6-year period (1990–1995) were respectively 0.16 and 0.06 kg ha^{-1} $year^{-1}$ (Campo et al. 2001a). There is no prior information on N deposition and N-fixation in the region.

The vegetation in the region is the SDTF (Rzedowski 1978). The forest is diverse in species composition, with approximately 750 species grouped in 108 families. Leguminoseae is the most important family, accounting for 15% of species (Lott et al. 1987). The more common species are *Caesalpinia eriostachys, Lonchocarpus eriocarinalis, Ipomoea wolcottiana, Bursera instabilis* Mc Vaugh & Rzedowski, *Jatropha malacophylla* Standl., *Croton chamelensis* Lott, *Cordia alliodora* (Ruiz & Pav.) Oken and *Spondias purpurea* L.

Experimental design

The experiment was carried out from July 2001 to July 2002, in a 90 × 50 m area on a slope facing mainly south (the slope angle ranges from 5 to 25°. Three blocks were chosen; each block contained 16 plots of size 5 × 6 m in which three types of mulch were placed (alfalfa straw, SDTF forest litter and white polyethylene) as well as control plots of bare soil. The blocks were spaced 2 m apart, and the plots were spaced 1.5 m apart, and set out lengthwise at 4 m intervals along the slope. To prevent possible leaching effects and water running from one plot into another, canals were dug (85 m long, 0.75 m wide and 0.60 m deep) running perpendicular to the slope.

Each plot with organic mulch was covered with 900 g dry matter per m^2 (forest litter or alfalfa straw; the leguminous *Medicago sativa* L.). This amount of mulch covered between 70 and 75% of the soil area. *Medicago sativa* is abundant in the region from cattle raising practices. The forest litter was a mixture of the SDTF plant species and was collected from the soil of the forest in the dry season at the end of May 2001. The litter consisted of all dead plant material lying on the forest floor, including freshly fallen litter and the more finely decomposed litter fraction. Saplings of three native species were used: *Ipomea wolcottiana* Rose (Convolvulaceae), *Lonchocarpus eriocarinalis* Micheli (Leguminoseae) and *Caesalpinia eriostachys* Benth (Leguminoseae). *Ipomoea wolcottiana* is a deciduous early successional species with fast growth rate; *L. eriocarinalis* a deciduous intermediate successional and N-fixer species with an intermediate growth rate, and *C. eriostachys* is a facultative deciduous, late successional species with a slow growth rate (Huante 1995). Twenty plants (0.66 plant m^{-2}), all 1-year-old, were transplanted into each plot with mulch or bare soil; a total of 240 plants were transplanted on July 22–25 2001, with 1.6 m distance between them. Each plot contained a single plant species. The experimental design was therefore a combination of 4 (3 mulches and bare soil) × 4 (3 species and without plants) factors with three replicates (3 blocks) = 48 plots. The selection of species was based on their high abundance in SDTF (Lott et al. 1987), their growth rates (Huante et al. 1995), and high production of seeds and germination fraction (I. Acosta, pers. comm. 2000).

Organic mulch analysis

Twenty samples of each organic mulch (i.e., alfalfa straw and forest litter) were oven dried (60°C for 48 h). Carbon was analyzed in an automated C-analyzer, after grinding a 5 g subsample for passage through a 100-mesh screen. The concentration of N and P was determined by Kjeldahl digestion; 0.5 g subsamples (also ground; 40 μm mesh size) were digested with 7 ml of concentrated H_2SO_4, 1.1 g of digest mixture (K_2SO_4 and Cu_2SO_4, 9:1), and 3 ml H_2O_2. Extracts and standards were analyzed colorimetrically in an autoanalyzer.

Soil sampling and analysis

Immediately prior to the experiment (July 2001), midway through the rainy season (September 2001) and the dry season (February 2002), three soil samples (5–10 cm depth) were collected randomly from each plot, combined in the field, and stored at 4°C for up to 48 h prior to processing. The upper 5–10 cm of the soil profile in this region is disproportionately rich in root biomass (~40% of total root biomass is in the upper 0.6 m of the soil profile, or until rock is reached, according to G. Barajas-Guzmán, unpublished data). Sampling dates were selected taking into account the effect of rainfall on the soil nutrient availability (Campo et al. 1998; Saynes et al. 2005). In the laboratory, the soils were homogenized by hand and were sieved (to 2 mm) in preparation for measurement of the soil volumetric water content (SVWC), which was determined from the weight difference between moist field samples and samples dried at 105°C for 48 h.

Soils collected at these two sampling dates were also measured for pH, and concentrations of soil organic C, total N and P, and concentrations of inorganic N (NO_3 and NH_4) and bicarbonate P. The soil pH was determined in water with a glass electrode in a soil:solution ratio of 1:2.5. Soil organic C was determined by humid oxidation with 5% K_2CrO_7, catalyzed with 5 ml of H_2SO_4; digestion was at 150°C for 30 min (Anderson and Ingram 1993). Total soil N was determined by the Kjeldahl method (Anderson and Ingram 1993). Total soil P was determined by the molybdenum method following perchloric acid and HNO_3 digestion (Anderson and Ingram 1993). Inorganic N concentrations were determined via extraction with 2 M KCl. Bicarbonate P was determined by the method of Murphy and Riley (1962) after 0.5 g soil had been shaken with 30 ml of 0.5 M $NaHCO_3$ for 16 h and centrifuged (10,000 rpm at 0°C for 10 min).

Sapling survival and growth

Sapling survival (as percentages of the initial numbers) was counted at the end of the rainy season (October 2001) and at the end of the experiment (July 2002). During the dry season it was not possible to determine with certainty which plants were alive, since they were leafless. Sapling growth was determined as the relative growth rate (RGR) based on height (measured from shoot base to apical meristem) and was calculated at the end of the rainy season (October 2001) and at the end of the experiment (July 2002). The RGR was calculated as follows (Hunt 1978):

$$\mathrm{RGR} = (\ln H_F - \ln H_I)/(t_F - t_I)$$

where H_F and H_I are the final and initial sapling heights; t_F is the final time (in days) and t_I is the initial time (in days).

Statistical analysis

A two-way (mulch and plant species) analysis of variance (ANOVA) was applied to the soil variables, sapling survival (data were transformed to arcsines of the square root of survival percentage) (Zar 1999) and to sapling RGR. Each plot included the slope as a co-variable. When the ANOVA analysis found significant differences between treatments, the Tukey Honest Difference Test was also applied. Finally, the *t* test was applied to evaluate differences in soil variables in each of the 16 combinations of mulch and species between seasons (rainy versus dry season). All statistical analyses were performed at a 95% confidence level.

Results

Characteristics of organic mulches

The concentrations of C, N and P varied significantly between the organic mulches (i.e., alfalfa straw and forest litter) (Table 1). Concentrations of C and N, and the C:P and N:P ratios were greater in alfalfa straw than in forest litter (by 5%, 30%, 45% and 60%, respectively). In contrast, the concentration of P and the C:N ratio were greater in forest litter than in alfalfa straw (by 40% in the case of phosphorus, and by 25% in the case of C:N ratio).

Soils

Prior to the experiment, there was no difference in SVWC, pH and the concentrations of soil organic C, total N and P, inorganic N and bicarbonate P between the plots (Fig. 1a and Table 2). Also, the slope was not significant in any result.

Application of mulch affects the SVWC. In the rainy season, plots with polyethylene mulch had

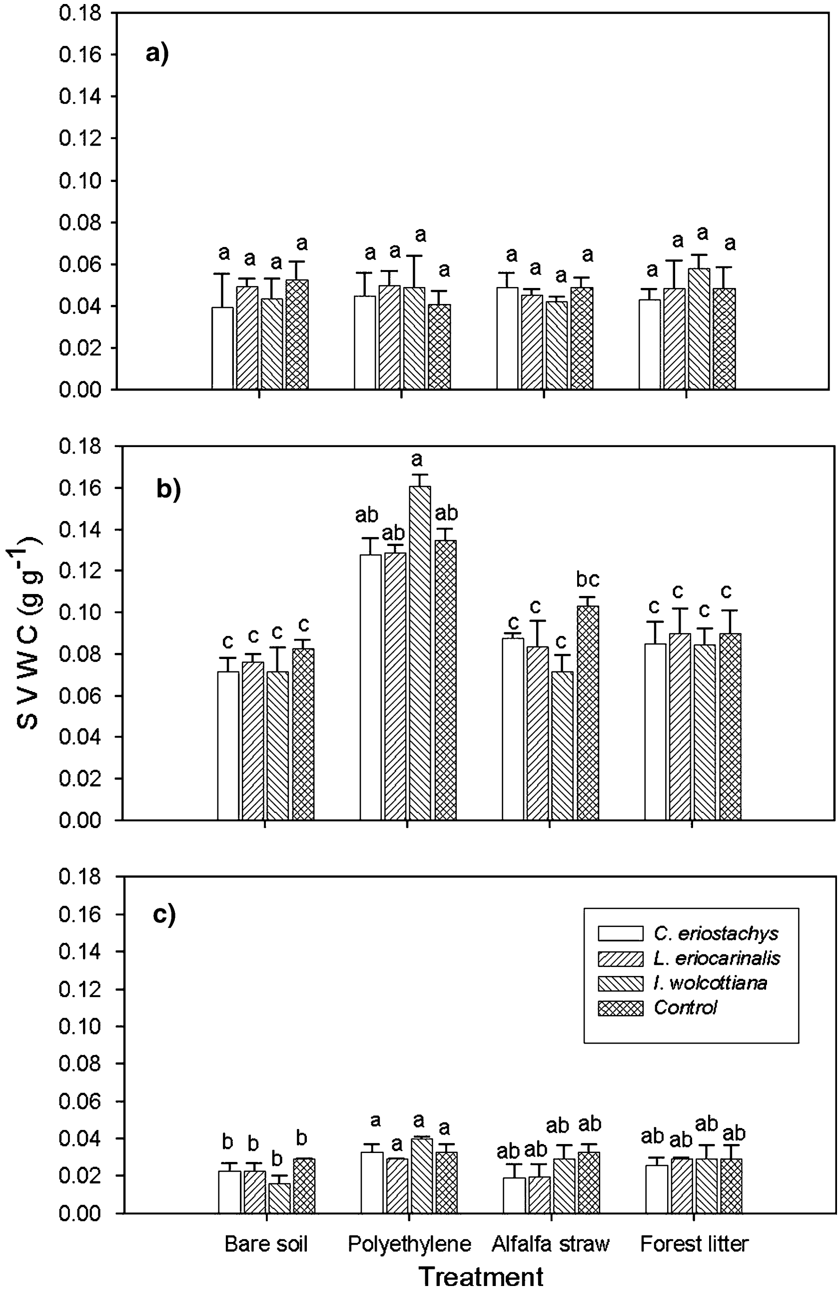
Table 1 Concentrations of C, N and P in organic mulches

	Alfalfa straw	Forest litter	Significance
C (%)	45.33 (0.41)	42.95 (0.23)	*
N (%)	1.94 (0.02)	1.36 (0.03)	***
P (%)	0.128 (0.004)	0.218 (0.006)	**
C:N	23.3 (0.4)	31.5 (0.8)	**
C:P	355.7 (11.43)	197.3 (6.58)	***
N:P	15.26 (0.75)	6.3 (0.12)	***

Values in parenthesis are 1 SE

Significance indicates the existence of differences between organic mulches at level of: *P < 0.01, **P < 0.001, ***P < 0.0001

Fig. 1 Soil volumetric water content (**a**) prior to the experiment, (**b**) in the rainy season, and (**c**) in the dry season. Lower case letters above columns indicate significant differences ($P < 0.05$). Error bars show ± 1 SE



significantly higher SVWC than control plots (bare soils) (Fig. 1b). In the dry season, SVWC increased in the order bare soil < alfalfa straw ~ forest litter < polyethylene (Fig. 1c). In contrast, SVWC in plant plots were not significantly different from values in plots without plants. As expected, the SVWC in the rainy season was higher (3-fold) than in the dry season (Fig. 1b, c).

Neither mulching nor plants significantly altered the soil pH or the concentrations of soil organic C and total soil N and P in the rainy and dry seasons (Table 3). The concentrations of soil organic C, total N and total P did not change with season. In contrast, there were significant differences between seasons in the soil pH in plots with alfalfa straw and *L. eriocarinalis*, in bare soil plots

Table 2 Soil pH, organic C, total and inorganic N, nitrate:ammonium ratio, and total and bicarbonate P in the study area prior to the experiment

pH	C mg g^{-1}	Total N mg g^{-1}	NO_3 µg g^{-1}	NH_4 µg g^{-1}	NO_3:NH_4	Total P mg g^{-1}	Bicarbonate P µg g^{-1}
7.1 (0.4)	20.32 (7.82)	2.16 (0.79)	10.04 (0.40)	9.16 (0.70)	1.23 (0.14)	0.47 (0.02)	13.52 (0.51)

Values in parenthesis are 1 SE

with *L. eriocarinalis*, and in plots with polyethylene and without plants (Table 3).

Mulching did not significantly alter the concentration of soil NO_3 in either season (Table 4). However, there was a significant effect of plant species on the soil NO_3 concentration. In the rainy season samples the soil NO_3 concentration was lower in plots with *I. wolcottiana* (6.72 ± 0.71 µg g^{-1}) than in plots with *C. eriostachys* (9.07 ± 0.42 µg g^{-1}). The soil NO_3 concentration measured in plots with *L. eriocarinalis* (8.21 ± 0.61 µg g^{-1}) and plots without plants (8.30 ± 0.63 µg g^{-1}) were not different from the *I. wolcottiana* and *C. eriostachys* plots. The interaction between mulch and plants was significant; soils under polyethylene mulch in the presence of *I. wolcottiana* had the lowest concentration of NO_3, and soils under polyethylene mulch without plants had the highest concentrations.

Soil NH_4 concentrations differed considerably between plots in both seasons (Table 4). In the rainy season, plots mulched with alfalfa straw had significantly higher concentrations of soil NH_4 (4.79 ± 0.58 µg g^{-1}) than plots mulched with polyethylene (3.03 ± 0.40 µg g^{-1}). Soils with the forest litter mulch and bare soil plots constituted an intermediate, statistically homogeneous group ($P > 0.05$).

In the dry season, the change in pattern and the concentration of soil NH_4 in plots mulched with forest litter (16.2 ± 0.6 µg g^{-1}) was clearly larger than with polyethylene mulch (13.7 ± 0.4 µg g^{-1}) and bare soil (12.1 ± 0.8 µg g^{-1}), but not significantly different from plots mulched with alfalfa straw (15.3 ± 0.8 µg g^{-1}). There was significant interaction between mulch types and plants in both seasons. The concentration of soil NH_4 was lowest in bare soil plots without plants, and

Table 3 Soil pH, organic C, total N and P concentrations in mulching plot experiments in rainy and dry season samples

Mulches/Species	Rainy season				Dry season			
	pH	C (mg g^{-1})	N (mg g^{-1})	P (mg g^{-1})	pH	C (mg g^{-1})	N (mg g^{-1})	P (mg g^{-1})
Bare soil								
Without plants	7.2 (0.3)	18.95 (5.46)	2.13 (0.53)	0.39 (0.01)	7.0 (0.1)	15.66 (3.21)	1.80 (0.31)	0.31 (0.08)
C. eriostachys	7.3 (0.2)	21.27 (3.73)	2.27 (0.23)	0.39 (0.07)	6.9 (0.1)	13.92 (4.27)	2.17 (0.20)	0.34 (0.04)
L. eriocarinalis	7.3 (0.3)	11.99 (1.04)	1.57 (0.08)	0.30 (0.01)	6.5 (0.3)	13.73 (1.71)	1.67 (0.34)	0.40 (0.15)
I. wolcottiana	7.3 (0.1)	20.69 (6.32)	2.07 (0.53)	0.32 (0.06)	7.0 (0.3)	20.11 (5.99)	2.27 (0.59)	0.33 (0.10)
Polyethylene								
Without plants	7.6 (0.3)	20.30 (7.1)	2.40 (0.001)	0.36 (0.02)	6.4 (0.1)	15.47 (7.0)	1.83 (0.66)	0.28 (0.05)
C. eriostachys	7.3 (0.3)	18.75 (5.08)	2.13 (0.53)	0.41 (0.05)	7.0 (0.5)	17.01 (6.56)	1.90 (0.68)	0.35 (0.08)
L. eriocarinalis	7.3 (0.2)	17.21 (2.34)	2.00 (0.14)	0.37 (0.10)	6.4 (0.5)	21.46 (2.18)	2.37 (0.25)	0.45 (0.06)
I. wolcottiana	7.6 (0.1)	21.07 (1.71)	2.73 (0.25)	0.41 (0.07)	7.0 (0.4)	19.91 (7.01)	2.13 (0.47)	0.39 (0.06)
Alfalfa straw								
Without plants	7.5 (0.2)	22.23 (2.61)	2.27 (0.53)	0.41 (0.02)	7.2 (0.5)	21.85 (4.91)	2.27 (0.35)	0.41 (0.05)
C. eriostachys	7.4 (0.2)	16.82 (2.97)	1.90 (0.38)	0.32 (0.05)	6.9 (0.2)	15.85 (1.56)	1.77 (0.18)	0.46 (0.11)
L. eriocarinalis	7.4 (0.2)	16.63 (5.29)	1.93 (0.39)	0.26 (0.01)	6.7 (0.1)	16.05 (2.24)	1.83 (0.30)	0.42 (0.09)
I. wolcottiana	7.3 (0.2)	17.98 (8.10)	2.00 (0.70)	0.32 (0.06)	7.0 (0.2)	19.53 (6.70)	2.10 (0.49)	0.44 (0.10)
Forest litter								
Without plants	7.5 (0.4)	17.98 (4.29)	2.27 (0.36)	0.40 (0.05)	6.5 (0.4)	16.43 (0.63)	2.03 (0.29)	0.40 (0.11)
C. eriostachys	7.3 (0.4)	11.79 (3.32)	1.57 (0.39)	0.31 (0.07)	7.3 (0.4)	18.17 (5.60)	1.90 (0.47)	0.32 (0.07)
L. eriocarinalis	7.2 (0.2)	23.97 (2.92)	2.60 (0.25)	0.32 (0.08)	7.2 (0.5)	18.56 (0.71)	2.23 (0.18)	0.26 (0.08)
I. wolcottiana	7.3 (0.6)	11.79 (1.85)	1.53 (0.30)	0.37 (0.05)	7.0 (0.3)	15.27 (2.37)	1.50 (0.44)	0.36 (0.08)

Values in parenthesis are 1 SE

Table 4 Soil inorganic N (NO_3 and NH_4) and bicarbonate P concentrations in mulching plot experiments in rainy and dry season samples

Mulches/Species	Rainy season				Dry season			
	NO_3 (μg g^{-1})	NH_4 (μg g^{-1})	NO_3:NH_4	Bicarbonate P (μg g^{-1})	NO_3 (μg g^{-1})	NH_4 (μg g^{-1})	NO_3:NH_4	Bicarbonate P (μg g^{-1})
Bare soil								
Without plants	8.38 (0.98)	2.19 (0.76)	4.22 (0.92)	10.07 (0.08)	6.17 (2.21)	12.53 (1.57)	0.50 (0.18)	11.70 (0.37)
C. eriostachys	10.19 (1.12)	4.65 (1.70)	2.95 (1.58)	12.03 (0.66)	6.15 (1.14)	8.98 (1.45)	0.73 (0.25)	12.97 (0.85)
L.eriocarinalis	8.26 (1.28)	2.71 (0.65)	3.14 (0.28)	14.80 (1.36)	6.70 (2.55)	12.04 (1.52)	0.54 (0.15)	11.93 (0.64)
I.wolcottiana	9.13 (1.83)	6.58 (2.72)	1.99 (1.19)	11.43 (0.53)	8.23 (1.53)	14.91 (1.13)	0.55 (0.07)	12.20 (0.61)
Polyethylene								
Without plants	11.94 (0.04)	2.67 (0.50)	4.67 (0.83)	15.77 (0.08)	9.55 (1.21)	12.67 (0.50)	0.76 (0.12)	12.10 (0.75)
C. eriostachys	9.52 (0.93)	3.92 (1.68)	3.17 (1.43)	15.13 (0.20)	6.19 (1.78)	13.26 (0.58)	0.47 (0.14)	12.17 (1.03)
L. eriocarinalis	6.01 (1.63)	2.29 (0.82)	2.79 (0.75)	13.50 (0.37)	6.53 (2.97)	14.29 (1.63)	0.48 (0.23)	16.03 (0.57)
I. wolcottiana	4.67 (1.08)	3.24 (0.64)	1.45 (0.17)	2.17 (0.57)	7.91 (1.10)	14.57 (1.21)	0.54 (0.07)	13.13 (1.20)
Alfalfa straw								
Without plants	4.67 (0.40)	3.31 (0.54)	1.44 (0.13)	11.53 (0.08)	4.31 (1.41)	14.98 (1.86)	0.29 (0.08)	14.23 (1.18)
C. eriostachys	8.45 (0.36)	6.42 (4.36)	1.57 (0.09)	16.20 (2.46)	8.41 (2.97)	18.08 (1.44)	0.45 (0.13)	14.50 (1.14)
L. eriocarinalis	10.04 (0.89)	6.87 (0.66)	1.49 (0.24)	11.07 (0.08)	6.01 (1.91)	15.54 (1.37)	0.38 (0.09)	12.60 (0.25)
I. wolcottiana	6.77 (2.00)	3.58 (1.98)	2.58 (1.14)	11.90 (0.55)	8.13 (1.09)	12.58 (1.63)	0.68 (0.19)	12.03 (1.27)
Forest litter								
Without plants	8.16 (1.39)	5.80 (0.35)	1.40 (0.16)	12.07 (0.08)	6.07 (0.81)	17.13 (1.47)	0.36 (0.06)	12.60 (0.93)
C. eriostachys	8.14 (1.26)	2.35 (0.47)	3.62 (0.87)	13.07 (0.47)	7.60 (2.59)	16.01 (1.99)	0.50 (0.22)	12.60 (0.74)
L. eriocarinalis	8.54 (1.03)	3.58 (0.36)	2.39 (0.16)	11.67 (0.35)	5.27 (0.55)	15.91 (1.54)	0.33 (0.02)	15.13 (1.05)
I. wolcottiana	6.31 (0.71)	2.92 (0.41)	2.25 (0.50)	14.50 (1.72)	9.58 (2.39)	15.59 (1.44)	0.60 (0.10)	14.17 (1.56)

Values in parenthesis are 1 SE

highest in plots with alfalfa straw mulch and with *L. eriocarinalis* in the rainy-season samples, whereas in the dry season the concentration was lowest in plots with bare soil and *C. eriostachys* and highest in plots mulched with alfalfa straw with *C. eriostachys*.

The nitrate:ammonium ratio in the rainy season differed significantly between mulches, but did not differ between plants (Table 4). The nitrate: ammonium ratio in plots mulched with alfalfa straw (1.77 ± 0.25) was significantly lower than in plots mulched with polyethylene and in bare soil plots (3.02 ± 0.47 and 3.07 ± 0.45, respectively). The nitrate:ammonium ratio in plots mulched with forest litter (2.41 ± 0.30) did not differ from values in other treatments. In contrast, the nitrate:ammonium ratio in the dry season did not differ significantly between mulches and plants. In general, the soil nitrate:ammonium ratio was larger in the rainy season than in the dry season (in 12 of 16 treatments).

The concentration of soil bicarbonate P in the rainy season varied significantly among mulches and plant species (Table 4). Soil bicarbonate P was higher in plots mulched with polyethylene (14.1 ± 0.4 μg g^{-1}) than in bare soil plots (12.1 ± 0.6 μg g^{-1}), whereas concentrations of bicarbonate P in plots with forest litter (12.8 ± 0.5 μg g^{-1}) and alfalfa straw (12.7 ± 0.8 μg g^{-1}) were as low as in the control (bare soil). On the other hand, the soil bicarbonate P concentration in plots with *C. eriostachys* (14.1 ± 0.7 μg g^{-1}) was higher than in plots without plants (12.4 ± 0.6 μg g^{-1}) and plots with *I. wolcottiana* (12.5 ± 0.5 μg g^{-1}). The concentration of bicarbonate P in plots with *L. eriocarinalis* (12.7 ± 0.5 μg g^{-1}) was similar to other plant treatments. Interaction between mulch and plants was significant; the lowest concentrations of bicarbonate P were found in bare soil plots without plants, and the highest concentrations in plots mulched with alfalfa straw with *C. eriostachys* plants. In dry season samples, in contrast, differences in bicarbonate P among mulches and plants were low and not significant. The bicarbonate P concentration in the soil did not differ significantly between seasons (Table 4).

Saplings

Plant survival varied significantly between species and mulch treatments at the end of the rainy season (Fig. 2a). Survival of saplings followed the order *L. eriocarinalis* < *C. eriostachys* < *I. wolcottiana*. *I. wolcottiana* and *L. eriocarinalis* in plots with mulching had significantly greater survival than plants in control plots (bare soil); in both cases, survival increased in the order bare soil < alfalfa straw < forest litter < polyethylene. In contrast, survival of *C. eriostachys* did not vary between mulch treatments.

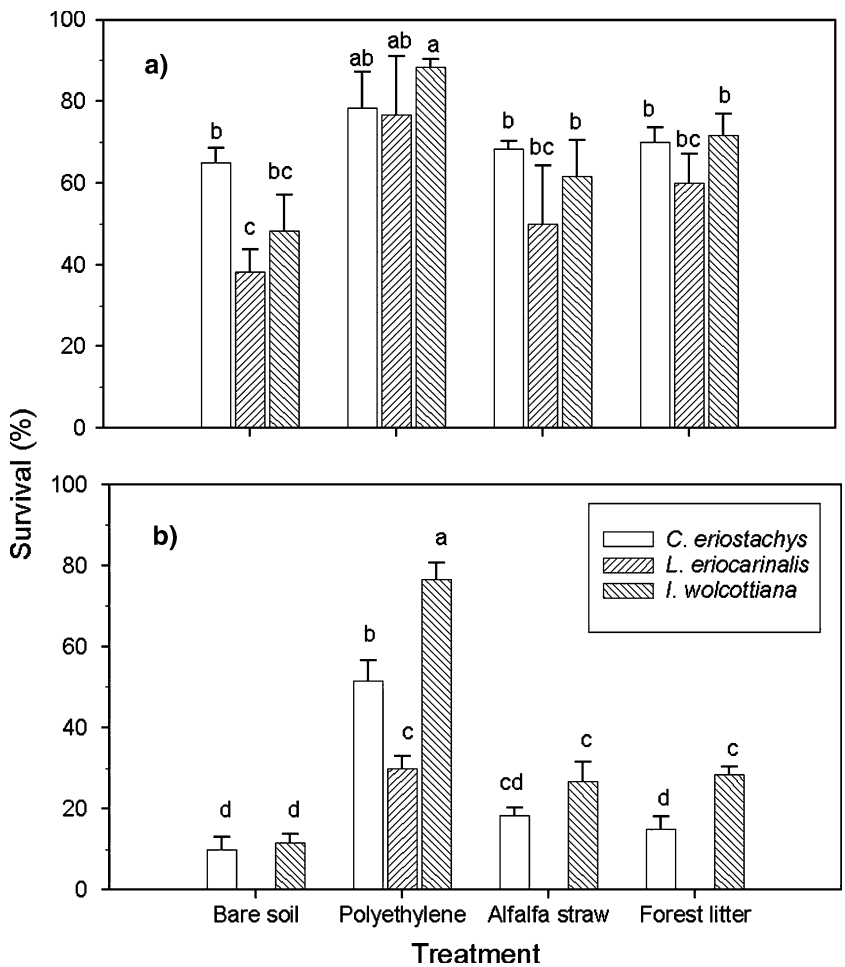
In the rainy season, the RGR of plants was in the order *L. eriocarinalis* < *C. eriostachys* < *I. wolcottiana* (Fig. 3a). Application of mulches produced a higher RGR for *I. wolcottiana* (bare soil < alfalfa straw < forest litter < polyethylene). Trends were similar for *C. eriostachys* and *L. eriocarinalis*, except that the RGR of both species in forest litter plots did not differ from zero.

After 8 months, differences in seedling survival and RGR among mulches and species were similar to those in the rainy season (Figs. 2b and 3b), although the survival proportion and growth rate was less in all treatments.

Discussion

We found that sapling survival in bare soil plots was very low; this is common in areas having strong seasonality in the rainfall pattern. Even in mature forests of SDTF the sapling survival is generally low. Kennard et al. (2002) reported survival values of 50% in a dry tropical forest in

Fig. 2 Sapling survival (**a**) at the end of the rainy season and (**b**) at the end of the dry season. Lower case letters above columns indicate significant differences ($P < 0.05$). Error bars show ±1 SE



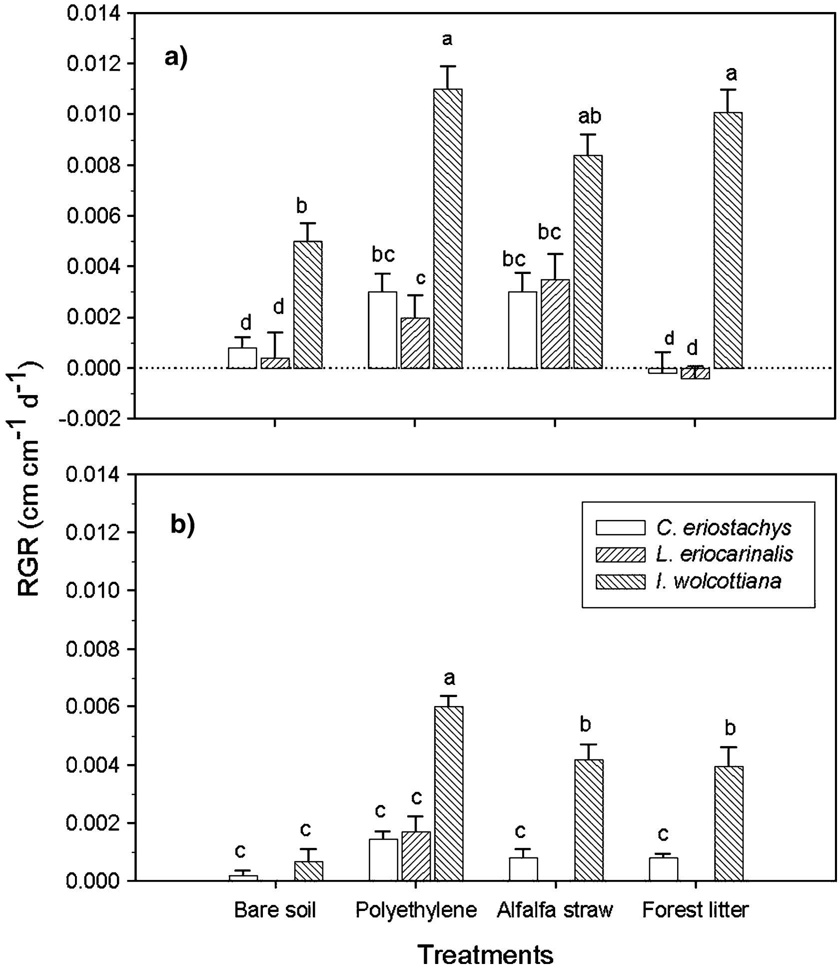


Fig. 3 Relative growth rates of saplings (**a**) at the end of the rainy season and (**b**) at the end of the dry season. Lower case letters above columns indicate significant differences ($P < 0.05$). Error bars show ± 1 SE

Bolivia, and Liberman and Li (1992) reported 38% survival in a dry semi-deciduous forest in Ghana. Our results for bare soil plots show a drastic reduction of survival, 3–4 times less than in mature forests. Of the three species studied, *L. eriocarinalis* died in bare soil; although the specimens survived until the end of the dry season, they had lost all their leaves after 3 days of transplantation, and after 5 days they had lost pieces of their stem. *Caesalpinia eriostachys* and *I. wolcottiana* plants performed poorly although they are a late and an early successional species. Differences in their successional state did not arise when environmental conditions were unfavourable.

Several soil conditions in bare soil may be unfavourable for sapling survival and growth, such as low soil water content, and low concentrations of soil NH_4 and bicarbonate P. When our values of soil organic C, total N and P, NO_3, NH_4 and bicarbonate P concentrations are compared with soil nutrient concentrations in mature SDTF in Chamela, Mexico, the present soil organic C and soil NH_4 concentrations were lower, e.g. our organic C value was 28% less than that reported by Jaramillo et al. (2003), and the soil NH_4 concentration is 70% less than that of Ellingson et al. (2000). Moreover, the concentration of soil NH_4 in our study was below the critical thresholds (25–50 μg g^{-1}) determined by Binkley and Vitousek (1989) for good plant performance. The change of land use clearly reduced the soil C and NH_4 content in this dry area. In our bare soil plots the air and soil temperature was very high (annual average 43.1 ± 0.5°C in the 30 cm above soil and 45.0 ± 0.7° C at 5–10 cm soil depth; Barajas-Guzmán and Barradas, submitted). Finally, sapling survival is likely to be higher on average than in our study year, in which the rainfall was only 50% of the long-term mean annual average.

When the soil was mulched, plant survival and growth increased (by 30–65% for survival and 8–9 times for plant growth, relative to plants in bare soil plots). Polyethylene was the best mulch for improving plant performance, with which the three species showed greatest survival and growth. A similar pattern of higher survival and growth in polyethylene than in organic mulches has been observed in the restoration of shrub vegetation with seasonal water stress (Hoy et al. 1994). In our study, plants responded to mulches according to the successional plant state; the late-successional species *C. eriostachys* exhibited lower survival and RGR than the early successional species *I. wolcottiana*.

Several studies have found that organic mulches increase the water content in the soil (Tilander and Bonzi 1997; Yohannes 1999), but in our study the SVWC increases only in polyethylene mulch plots (doubling the bare-soil values). The high SVWC in polyethylene mulch could be due to the large amount of solar radiation reflected and the reduced water evaporation that occurs under polyethylene coverage. Barajas-Guzmán and Barradas (submitted) reported that the average net radiation during the study was 479 W m^{-2} in polyethylene plots, 566 W m^{-2} in bare soil, 585 W m^{-2} in alfalfa straw and 601 W m^{-2} in plots mulched with forest litter. Moreover, the air temperature (30–35 cm above soil) and soil temperature (5–10 cm depth) in plots mulched with polyethylene were lower than those in plots with alfalfa straw or forest litter (air temperatures of 39, 42 and 42°C respectively, and soil temperatures of 37, 38 and 40°C).

Both organic and inorganic mulches increased the soil NH_4 and bicarbonate P concentrations. Alfalfa straw (high quality C:N 23.3) and forest litter (medium quality C:N 31.5) were fragmented and had disappeared a year after application, suggesting that the N and P released during plant tissue decomposition were incorporated into the soil. The increase in the concentration of soil bicarbonate P under polyethylene mulch apparently occurred because the increase in soil water content enhanced P availability (Sardans and Peñuelas 2004).

The effect of plants on the amount and dynamics of soil nutrients has been well documented (e.g. Binkley and Giardina 1998; Berendse 1998). Our study found that tree saplings influenced the concentrations of soil mineral N and bicarbonate P. Interestingly, although soil NO_3 and bicarbonate P was affected by both *I. wolcottiana* and *C. eriostachys*, the two species gave opposite patterns. Plots with *I. wolcottiana*, a species with the highest RGR (in our study and that of Huante et al. 1995) had the lowest concentrations of soil NO_3 and bicarbonate P, whereas plots with *C. eriostachys*, a species of low RGR (Huante et al. op. cit.), had the highest concentrations of both nutrient forms. This confirms the distinct use of resources by plants according to their successional mechanisms.

In conclusion, our results show that polyethylene was the most effective mulch type, and that early successional species of high growth rate (e.g. *I. wolcottiana*) have the best survival and growth in such areas. Mulching may therefore be an important technique for restoration of dry areas, since it has a positive effect on variables favorable to successful plant establishment during reforestation.

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