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Ecological suitability and tree seedling survival in the Bolivian altiplano

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ABSTRACT. Tree seedling survival rates are low in the dry, harsh climate of the Bolivian altiplano. We tested two species, *Polylepsis tarapacana* and *Cupressus macrocarpa,* using four microcatchment planting methods and a control to determine if species survival could be improved. The control improved surface infiltration rates but provided no protection from wind and cold. The four sub-surface planting methods increased soil moisture and mitigated cold, desiccating winds. The native species, *P. tarapacana*, showed better survival than the non-native one. All planting methods showed excellent survival rates for *P. tarapacana*, as all methods improve rainfall infiltration in relatively poor soil. Pit planting proved to be more successful for *C. macrocarpa* than other planting methods, probably due to the protection it provides from climatic stress during the winter months and the increased soil moisture. While modifying the local micro-ecological conditions improves seedling survival, selecting ecologically suitable species is a more successful strategy for tree planting.

[Keywords: *Polylepsis tarapacana, Cupressus macrocarpa*, microcatchments, agroforestry]

RESUMEN. Adaptabilidad ecológica y supervivencia de semillón de árboles en el altiplano Boliviano: En el clima seco y pesado del altiplano Boliviano, las tasas de supervivencia de germinación en árboles son bajas. Mientras granjeros y agentes de extensión describen la necesidad de árboles, recientes trabajos de forestación han tenido relativo fracaso. Esto se ha debido en parte a la selección de especies, y en parte, a las técnicas de plantación. Ambas fallas constituyen prueba de la falta de combinación de las condiciones ecológicas locales del altiplano Boliviano. Nuestro estudio se llevo a cabo en el Centro Experimental Agropecuario Condoriri, Departamento de Oruro, Bolivia. Probamos dos especies, *Polylepsis tarapacana* y *Cupressus macrocarpa,* utilizando cuatro métodos de plantación con micro-captación y con un control para determinar la posibilidad de mejorar la supervivencia de las especies. El control, un método estándar de plantación a nivel del suelo, mejoró las tasas de infiltración, pero no pudo proporcionar protección del viento y frío. Los cuatro métodos de prueba fueron de plantación sobre la superficie y todos incrementaron la humedad de la tierra. Planteamos la hipótesis de que los cuatro métodos disminuirían el impacto de los fríos y disecantes vientos. Las especies nativas, *P. tarapacana*, mostraron mayor supervivencia que las exóticas. Todos los métodos de plantación mostraron excelentes tasas de supervivencia para *P. tarapacana*, y mejoraron la filtración en tierra relativamente pobre. Para *C. macrocarpa*, la plantación en una cavidad de la tierra demostró ser más exitosa que otros métodos de plantación. Esto probablemente se debió a la protección de la presión climática que recibe durante los meses de invierno y el incremento de humedad en la tierra. Los otros métodos de prueba consistieron en trincheras que dieron menos protección que una pequeña cavidad (de 30 centímetros). Modificar las condiciones micro-ecológicas mejorará la supervivencia de la semilla; la selección de especies adecuadas es una estrategia más exitosa para la plantación de árboles.

[Palabras clave: *Polylepsis tarapacana, Cupressus macrocarpa*, sistemas de microcaptación, agroforestería]

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INTRODUCTION

The Bolivian altiplano is experiencing new challenges resulting from land degradation and increased population pressures. According to INE (1993), the overall human population density (people/ha) for the altiplano region has increased from 4.86 to 9.44 since 1950. Since that time, land holding size has decreased and marginal grazing lands are now cultivated. A substantial portion of these lands contain poor soils, low vegetative cover, and high erosion rates. Coupled with low annual rainfall and overgrazing of increasingly larger areas, the Andean farmer has seen a steady drop in soil quality and, as a result, farm production. Although farmers in this area want to use modern agroforestry practices, low seedling establishment and growth rates make their incorporation into realistic farming systems difficult.

The ecological setting of the altiplano demands care when selecting species for planting. Long-term climate records, derived from a 50.000 year data set of lake-bed cores, indicate substantial variation in both temperature and rainfall over the altiplano (Baker et al. 2001). Plant species have adapted to these long-term cycles, including the current drier climate. On an annual basis, weekly weather variations may also stress plants which are not adapted to rainfall and temperature variation. The majority of the altiplano's precipitation falls during the summer (December through March), but occurs as sporadic, intense thunderstorms scattered over a one-week period. The intervening periods between sets of thunderstorms are often longer than the rainy periods (Garreaud 2000). Again, native plants are adapted to the variable climate. Much of the altiplano and *paramo* is grassland. Attempts at planting *Pinus radiata* have not always succeeded. *Pinus radiata* requires substantially more water than native grassland (Farley et al. 2004). In contrast, ecological adaptations, especially high production rates, of *Polylepsis quadrijuga* allow the species to survive in the *paramo* of Columbia, an environment dominated by grasses (Velez et al. 1998). As with many high altitude environments, the altiplano has rapid and intense daily temperature variations (Friend & Woodward 1990). Altiplano species have adaptations which allow them to survive even under such extreme temperature changes (Rada et al. 1985).

Successful silvicultural activities in this zone have largely been limited to small plantings in protected areas such as home patios or village squares. In this region, the careful selection of species adapted to the local environment and the development of microcatchment systems for individual seedlings, may prove to be an effective strategy for increasing general agricultural production and improving land quality. Previous work in the altiplano includes numerous outplantings with poorly selected species and without microcatchments, and these initial trials had unsatisfactory survival rates (Cohen 2002). Increase in subsurface water yield is well documented from microcatchments (Slayback & Cable 1970; Ehrler et al. 1978; Sharma et al. 1986; Boers et al. 1986). We hypothesized that tree seedling survival in the altiplano will increase when using a microcatchment system to improve the microenvironment and by selecting species which are adapted to the local environment.

Study area

The study was conducted in the community of San Antonio de Condoriri, in the Cercado Province of the Department of Oruro, Bolivia. The experimental planting trials were conducted at the Centro Experimental Agropecuaria Condoriri (CEAC), also known as the Agricultural Research Station at Condoriri. CEAC is located on the Bolivian central altiplano (17°31´ S; 67°17´ W). The center is situated at an altitude of 3830 m.a.s.l. The long-term average for precipitation is approximately 350 mm per year and daily mean temperatures range from 6°C to 13°C, although winter temperatures may fall to -18°C (Cardenas 2001). Precipitation is unimodal in its distribution with the majority arriving in the summer months of December through March, which corresponds with the agricultural growing season. The total precipitation accumulated during the study period was 448 mm, with approximately 80% of the precipitation arriving in the months of January through March (Figure 1). The mean daily air temperature for the trial period was slightly below the normal with the largest difference occurring in the month of July when temperatures were on average 4°C cooler than the long-term daily average (Figure 2). During the trial, the relative humidity was approximately 45%, the average evaporation rate was 4.2 mm/day, and the dominant wind pattern was from the north (Cardenas 2001).

This experiment was conducted on 1.3 ha of land in the CEAC. Natural vegetation consists largely of prairie grasslands intermixed with shrubs and bushes. The clay content of the soil is high and infiltration rates measured with a double-ring infiltrometer (Bouwer 1986) on undisturbed sites are between 1 and 2 mm per hour (Cohen 2002).

METHODS

The experiment used replicated blocks of five microcatchment designs and two species for a total of 10 treatments. We conducted a two-way ANOVA test, a means model (Milliken & Johnson 1984), using number of surviving trees as the dependent variable in the 10 treatment combinations. Two commonly used species of trees, one native and one non-native, were selected for this experiment. The native species selected was *Polylepsis tarapacana* (Hieron) and the non-native one selected was *Cupressus macrocarpa* (Hart). The response variable for this study was the number of surviving individuals. The means model was used to identify differences between treatment and species combinations using Tukey's test (Steel & Torrie 1960). The data analysis for this paper was generated using SAS software, Version 9 for Windows. For the purposes of statistical analysis, the number of surviving individuals was converted to a proportion and transformed with the arcsine square root transformation. Homoscedasticity was not evident in the data (Steel & Torrie 1960). We tested the hypotheses that survival rates of native species will be significantly higher ($p < 0.05$) than non-native ones, and that protection and added soil moisture provided by microcatchments will also increase overall survival rates.

Polylepsis tarapacana

P. tarapacana grows at a higher altitude than any other tree species in the altiplano. Forests in which these trees are the dominant species

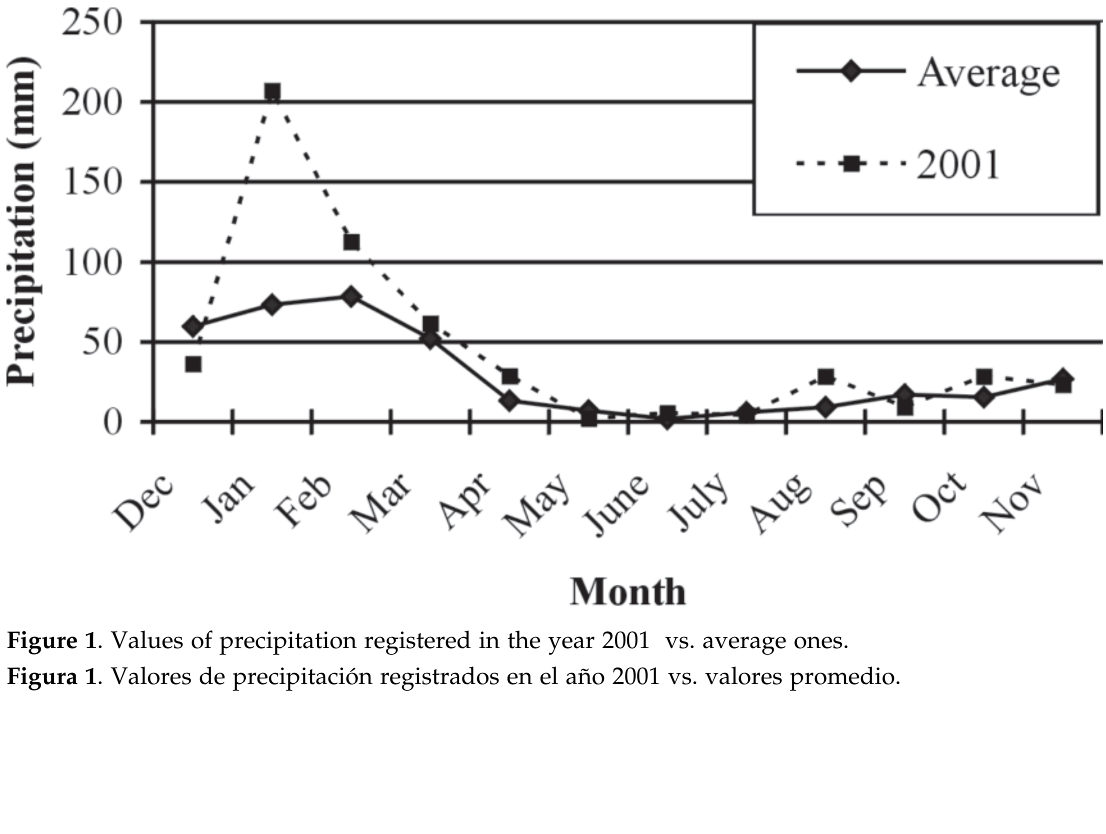

Figure 1. Values of precipitation registered in the year 2001 vs. average ones.

Figura 1. Valores de precipitación registrados en el año 2001 vs. valores promedio.

are considered to be some of the most endangered forest ecosystems in South America (Hjarsen 1998). *P. tarapacana* is commonly known as Kehuiña, Kewiña, Queñua, Keuña or Q'iwiña and is typically found in Bolivia along the central and southern high plains regions at altitudes ranging from 4100-5200 m.a.s.l. (Argollo et al. 2000; Loayza et al. 2000; Rada et al. 2000). The species is described by Fjeldså (1992) as appearing in either a bush or tree form with a twisted trunk, evergreen foliage, dense nanophyllus leaves and often associated with a large amount of dead twigs and other organic material at its base. The bark is generally easy to remove but is quite thick and heavily laminated. Although generally small in height, some individuals have been observed to reach up to 20 m. Cárdenas (2001) estimated that at higher altitudes *P. tarapacana* has a height growth rate of only 14 mm per year with the majority of that growth occurring in the summer months from January to March. Using increment core counts, Argollo et al. (2000) discovered that *P. tarapacana* can reach ages of more than 230 years.

Researchers have found that *P. tarapacana* can withstand sharp temperature variations and extremely high altitudes. Rada et al. (2000) observed that injury temperatures for *P. tarapacana* ranged from -18°C to -23°C. Among altitudinal distributions, Gonzales et al. (2000) discovered that populations at or above 5000 m.a.s.l. exhibited higher leaf area and higher leaf dry weight, increased levels of chlorophyll, carotenoids, glucose, fructose and sucrose, and larger numbers of palisade cell. Garcia-Nuñez et al. (2000) also found differences in water potential and stomatal conductance at various altitudes. CO_2 levels remained unchanged and *P. tarapacana* showed that "a rapid recovery after night freezing permits a favorable carbon balance at leaf level all year round". These adaptations make the plant well-suited to survival in the Bolivian altiplano.

Cupressus macrocarpa

C. macrocarpa, otherwise known as Monterey Cypress, originates from Monterey Bay in the

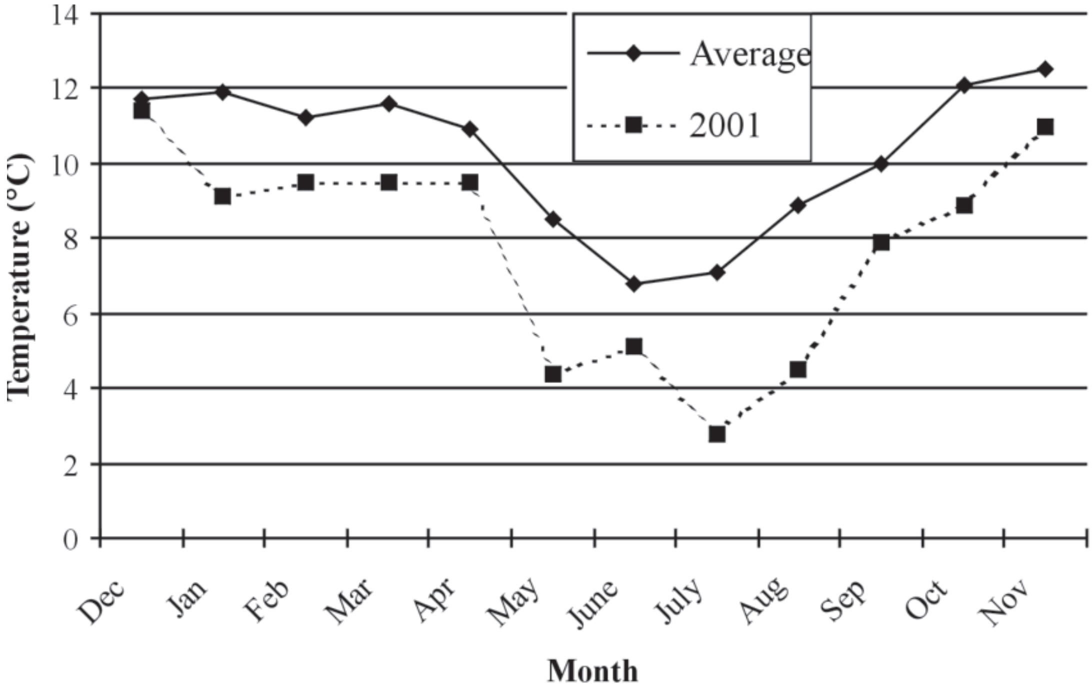

Figure 2. Values of temperature registered in the year 2001 vs. average ones.
Figura 2. Valores de temperatura registrados en el año 2001 vs. valores promedio.

northern coast of California, USA. Currently, there are only two native groves of *C. macrocarpa* in the entire world with both occurring in the Monterrey region (Montara 2002). C. *macrocarpa* ranges in height from 21-27 m although when transplanted from its native area it has been known to reach heights of more than 30 m (Gilman & Watson 1993; Floridata 2002). Gilman and Watson (1993) describe the species as having a columnar, pyramidal shape, straight trunk, moderate density, and simple, scale-like opposite/subopposite leaf arrangement.

C. macrocarpa grows in full sun on a variety of soils including clay, loam and sand. It has got a high aerosol salt tolerance. Miller & Knowles (1990) state that *C. macrocarpa* is capable of surviving in a wide variety of climates and can withstand up to -10°C of ground frost. They further note that *C. macrocarpa* is generally better than average on cold, dry sites, or any area where nitrogen availability is low, and that individuals of this species respond well to shelter but can withstand wind. Again, these characteristics seem to make *C. macrocarpa* a suitable candidate for planting in the altiplano. However, the species typically grows at a lower altitude and so is somewhat off-site at the experimental site.

Microcatchment Treatments

Ten randomized, replicate blocks of the control and microcatchment treatments were laid out sequentially on a hillside of approximately 7% slope. Three individuals of each species per microcatchment treatment per block were located (Table 1). The microcatchment treatments were spaced along the contour 10 m down slope from the next treatment so as to provide for an adequate water catchment area (3 m microcatchment: 10 m untreated soil surface). The tree seedlings were spaced 1.5 m apart within the microcatchment treatments and 1.5 m from the plot edges. In order to exclude grazing animals from the study area, a barbed wire fence was set up around the outside perimeter. The five microcatchment treatments within each block had the following specifications (Figure 3):

1.) Microcatchment Treatment 1 was the control. Trees were planted at ground level with no protection from the elements. The excavation of the planting hole served as the only ground preparation.

2.) Microcatchment Treatment 2, known as the pit planting method, was a simple hole dug in

Table 1. Experimental Design. Q = *Polylepsis tarapacana*; C = *Cupressus macrocarpa*. 1 = control; 2 = pit planting; 3 = basic trench system; 4 = widened trench system; 5 = slanted trench system.

Tabla 1. Diseño experimental. Q = Polylepsis tarapacana; C = Cupressus macrocarpa. 1 = control; 2 = plantacion en hoyo; 3 = sistema básico de trinchera; 4 = sistema de trinchera ensanchada; 5 = sistema de trinchera biselada.

Treatment order	Tree order	Treatment order	Tree order
Block 1		Block 2	
4	QCQCQC	3	CCQQCQ
2	QQCQCC	4	CCCQQQ
5	QCCQCQ	2	QCCQQC
3	QCQQCC	1	QQCCQC
1	CQQCQC	5	CQCQCQ
Block 3		Block 4	
5	CQQCCQ	2	CCCQQQ
3	QCQQCC	5	CCQCQQ
4	QCCQQC	1	QCCQCQ
1	CQCQQC	3	QCQQCC
2	QCQQCC	4	CQCQCQ
Block 5		Block 6	
4	CQQQCC	2	CQCQCQ
1	QQCCQC	1	QQCQCC
3	CQQQCC	4	QCCQQC
2	QCQCCQ	3	CCQQCQ
5	QCCQCQ	5	QQCCQC
Block 7		Block 8	
4	CQQCQC	4	QQQCCC
3	CQCQCQ	5	QCQCQC
2	QCQCQC	2	QQCCCQ
5	CQQCQC	3	CQCQQC
1	QCCQQC	1	CCCQQQ
Block 9		Block 10	
1	QCQCQC	2	CCQQQC
3	QCQCQC	4	QQCCCQ
5	QQQCCC	3	QQCQCC
2	QCCQCQ	1	CCQQCQ
4	QQCCCQ	5	CQCQQC

the ground with one hole dug per seedling. The hole was dug to an additional depth of 30 cm. The seedling was planted 30 cm below ground to provide protection from the elements while still giving the seedlings access to sunlight.

3.) Microcatchment Treatment 3 was a basic trench system dug to a depth of 30 cm.

4.) Microcatchment Treatment 4 consisted of a widened trench basin (approximately 60 cm wide) with the trench depth still maintained at 30 cm. The increased width of the trench was constructed so as to allow for a larger collection area of water runoff within the microcatchments.

5.) Microcatchment Treatment 5 consisted of a slanted trench system similar to trench number 4 but with an additional trench dug 30 cm deeper in the center of the trench system.

At the time of planting, approximately 2.5 kg of sheep manure was applied to each seedling to minimize adverse effects of transplanting. No further fertilizer was applied throughout the remainder of the study and the trees were not watered. The number of surviving seedlings was counted every 75 days. The perimeter fences were checked daily. Trees were judged to be surviving if they contained green leaves and flexible, green trunks (underneath bark). Trees considered to be on the edge of dying were still considered alive until at least the next data collection period if they exhibited these characteristics.

RESULTS

Polylepsis tarapacana had high rates of survival across all microcatchment treatments while *Cupressus macrocarpa* exhibited low survival rates, except in microcatchment treatment number two (Table 2). Overall, tree survival for *Polylepsis tarapacana* was 90% significantly higher ($F = 13.24$; $p = 0.005$) than the 21% survival rate for *Cupressus macrocarpa*. The greatest mortality of *P. tarapacana* occurred during the first 3 months following planting. In contrast, mortality of *C. macrocarpa* was highest in the last 3 months of the study (August until November), the time when climatic conditions are most severe and least similar to conditions in the natural range of *C. macrocarpa*.

Of the five different microcatchment treatments within this experiment, only treatment number two, pit planting, improved survival of cypress seedlings significantly ($p < 0.05$). ANOVA results indicated that survival of *Polylepsis tarapacana* was significantly higher than *Cupressus macrocarpa*, and that the effect of the microcatchment treatments also were significant. Treatment effects were significant ($p < 0.05$), as well as species effect ($p < 0.05$). The treatment-species interaction was also significant ($p < 0.05$). The results indicate that for cypress, the survival rate for microcatchment treatment two (pit planting) was significantly higher than for the other four treatments.

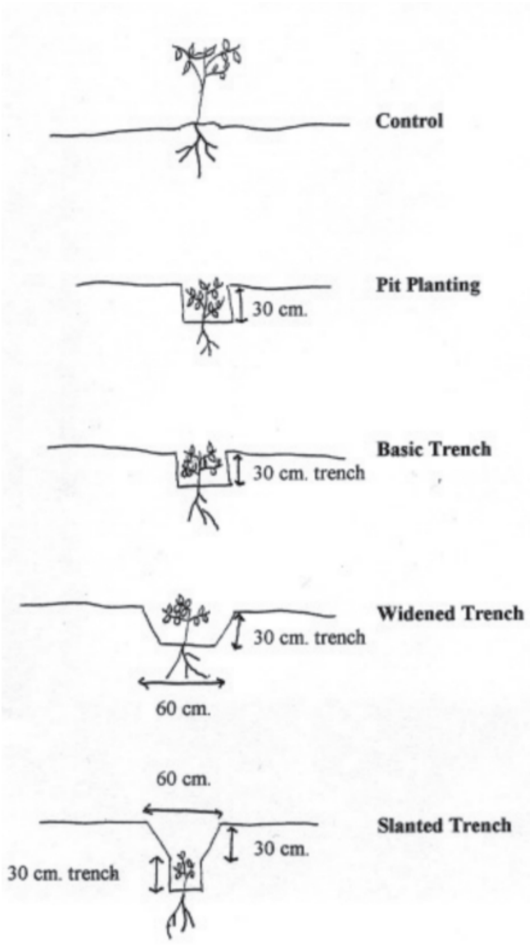

Figure 3. Microcatchment Treatments.
Figura 3. Tratamientos de microcaptación.

The ANOVA model indicated that for *Polylepsis tarapacana*, differences were not significant between any of the microcatchment treatments (F = 1.14; p = 0.005; df = 4, 32). *Cupressus macrocarpa* treatments were determined to be significant, apparently resulting with a higher seedling survival rate for microcatchment treatment two (pit planting) (F = 28.53; p = 0.005; df = 4, 32).

DISCUSSION

There were important differences between the native and introduced seedlings. Survival of native *P. tarapacana* was independent of microcatchment treatment effects. Conversely, the survival of *C. macrocarpa* increased significantly in the pit planting treatment. Possible explanations for these differences lie in the evolutionary origins of each species. *C. macrocarpa* evolved along the coastal regions of northern California where ecological conditions important to natural selection are quite different from the Bolivian altiplano. The seedlings of *C. macrocarpa* were desiccated and burned as a result of the high winter winds and sharp temperature variations. Based on prior field observations, it can be postulated that other commonly used introduced tree species exhibit similar poor establishment rates. Given the ecological constraints imposed on trees by the variable climate of the altiplano, it is reasonable to presume that seedlings in microcatchments which receive more water and provide shelter from wind and cold will be more likely to survive than seedlings planted in the ground surface with no protection. Microcatchment treatment two was effective at providing more water and better protection for *C. macrocarpa*. Trenches would also provide less wind protection than the pit planting method when wind direction is parallel to the length of the trench, suggesting that wind speeds in pits are less than those in trenches.

P. tarapacana exhibited substantially higher survival rates than *C. macrocarpa* and there was no difference among the microcatchment treatments for *P. tarapacana*. The initial mortality of *P. tarapacana* was probably due to poor planting techniques rather than environmental factors since survival rates were relatively high in the latter part of this study. The 90% survival rate indicates that the soil preparation method of all microcatchment treatments, including the control, helped *P. tarapacana* survive. Unprotected seedlings of both species are often grazed, so animal exclusion also played a role in seedling survival.

CONCLUSIONS

Two major ideas emerged from this study regarding the establishment rates of planted tree seedlings in the altiplano of Bolivia. A well-adapted native species had higher survival rates than a non-native one, regardless of the microcatchment method. This indicates that life-history traits are important. Correctly selecting native species that are adapted to the local growing conditions can dramatically improve survival rates. Secondly, using the pit planting microcatchment design can significantly improve the survival of non-native species. This design improves micro-scale ecological conditions such as increased availabil-

Table 2. Percentage of survival by species and Microcatchment Treatment (30 seedlings planted per treatment).

Tabla 2. Porcentaje de supervivencia por especie y tratamiento (30 semillas plantadas por tratamiento).

Microcatchment treatment	*Polylepsis tarapacana*	*Cupressus macrocarpa*	Total	% Survival
Treatment 1	26	1	27	45
Treatment 2	28	20	48	80
Treatment 3	25	5	30	50
Treatment 4	29	2	31	51
Treatment 5	27	3	30	50
Total	135	31	166	55

ity of water and protection from strong winds and severe fluctuations in air temperature. This study also showed that the introduction of a proper microcatchment system to this region could improve tree establishment rates for non-native species. Not only does the most enclosed system reduce cold and wind damage, but microcatchments increase water availability while ground preparation increases infiltration rates.

If introduced species are to be used over native ones, more emphasis on adaptability of these introduced species is needed. Ideas such as these are slowly beginning to take root. In a study on the adaptability of forage crops, Wheeler et al. (1999) used simulations to compare how various agricultural species from similar climatic zones around the world would match the climate found in the Bolivian Andes. Their findings indicate that, in addition to the native species currently used, two cover crops from Nepal could successfully be integrated into Bolivian farm systems located at altitudes of around 3000 m.a.s.l.

Throughout the world, a number of climatic zones exist which are somewhat comparable to the Bolivian altiplano. Examining tree species from areas such as the Himalayan mountain ranges or the Sierra Nevada Mountains, could yield species more suited for the conditions that exist in the altiplano. Trees could still be selected based on desired characteristics but such selection should be restricted to similar arid geographical zones. The introduction of species more suitably adapted to the altiplano and the utilization of microcatchment systems could greatly increase establishment rates for native and non-native trees.

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