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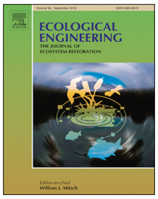

Restoring oak forests on bare ground using topsoil translocation

David Douterlungne[a,b,*], Guadalupe María Cortés Martínez[a], Ernesto Iván Badano[a], Jorge Alberto Flores Cano[c], Joel David Flores Rivas[a]

[a] *CONACYT Research Fellow, Instituto Potosino de Investigación Científica y Tecnológica, A.C. (IPICYT), Department of Environmental Sciences. Camino a la Presa San José 2055, Colonia Lomas 4ta Sección, C.P. 78216, San Luis Potosí, SLP, Mexico*

[b] *Instituto Potosino de Investigación Científica y Tecnológica, A.C. (IPICYT), Department of Environmental Sciences. Camino a la Presa San José 2055, Colonia Lomas 4ta Sección, C.P. 78216, San Luis Potosí, SLP, Mexico*

[c] *Facultad de Agronomía y Veterinaria, Universidad Autónoma de San Luis Potosí, Km. 14.5 Carretera San Luis-Matehuala, Apdo. Postal 32, Soledad de Graciano Sánchez, C.P. 78321, San Luis Potosí, SLP, Mexico*

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ABSTRACT

Seedling establishment in degraded Oak forests is often hampered by harsh soil conditions, which may take decades to recover. Translocating the top soil from old-growth healthy forests to severely impaired sites can improve environmental conditions and eventually trigger self-repairing forest succession. We tested the potential of this strategy to enhance the seedling establishment of three oak species (*Quercus eduardii* Trel., *Quercus viminea* Trel. and *Quercus resinosa* Liebm.) in a fragmented seasonally dry oak forest with severely weathered soils in Mexico. We transferred old-growth forest topsoil with and without leaf litter to a degraded clearing. To separate habitat from soil effects, we also moved topsoil from the clearing into the old-growth forest. The effects of soil translocation on seedling establishment varied according to life-stage (acorn, seedling, and young sapling), season (rainy vs dry) and site (clearing vs forest). In the clearing, transferred forest topsoil covered with leaf litter yielded the maximum germination probability rates, which were 7 ± 1% higher than in native weathered soil. Once seedlings emerged, survival probability decreased in the transferred soil in both sites, *i.e.* the weathered clearing soil in the forest habitat, as well as the forest soil in the clearing. Furthermore, transferring forest soil and leaf litter enhanced initial seedling growth in the clearing, increasing growth rates by 60 ± 5% compared to native weathered soil. Increased soil moisture due to soil translocation enhanced seedling establishment in the clearing, but decreased germination and survival rates in the forest. Our results suggest a dynamic water stress mechanism: (1) lack of moisture in soils with poor water retention capacity during the dry season; and (2) water excess during the rainy season in more mesic soil habitats. Given the elevated cost of translocating topsoil and the damage this causes at donor-sites, we recommend considering this intervention only for sites with reduced water retention capacity, prolonged dry seasons and slow soil formation.

1. Introduction

Forest ecosystems are under increased human pressure. More than half of original tropical forests are already lost, while 50% of the remaining forests are fragmented and degraded (Asner et al. 2009). Forests are mainly substituted by agriculture lands, which now occupy > 40% of the world's surface (Foley et al. 2005). As forests are of paramount importance in maintaining the world's biodiversity and ecological services, their conservation and restoration are considered global priorities (Aronson and Alexander 2013).

Several ecological barriers constrain forest regeneration in landscapes where forest and agricultural land-uses co-exist. Lower densities of mature trees result in reduced pollen flow across individuals and hence, less seed formation (Knapp et al. 2001). Furthermore, zoochoric seed dispersion can be low as faunal assemblages are often modified or reduced due to poaching or habitat destruction (López-Barrera et al. 2007). Seeds that do get dispersed face harsh environmental conditions. Germination and establishment of forest species are more likely to occur in moist sites with loose soils where emerging radicles easily penetrate the substrate to find water and nutrients (Tripathi and Khan 1990). However, soils in man-made clearings are often heavily disturbed. The absence of leaf litter and canopy cover

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[*] Corresponding author at: CONACYT Research fellow, Instituto Potosino de Investigación Científica y Tecnológica, A.C. (IPICYT), Department of Environmental Sciences. Camino a la Presa San José 2055, Colonia Lomas 4ta Sección, C.P. 78216, San Luis Potosí, SLP, Mexico.

E-mail addresses: david.d@ipicyt.edu.mx (D. Douterlungne), maria.cortes@ipicyt.edu.mx (G.M. Cortés Martínez), ernesto.badano@ipicyt.edu.mx (E.I. Badano), jorge.cano@uaslp.mx (J.A. Flores Cano), joel@ipicyt.edu.mx (J.D. Flores Rivas).

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increases water run-off and nutrient leaching (Foley et al. 2005), while cattle trampling or heavy machinery used for agricultural purposes compacts soil and reduces its water retention capacity (Ampoorter et al. 2011). These conditions further enhance the barriers for forest recovery and hence represent amplifying feedbacks of forest degradation (Hobbs and Suding 2009; Suding and Hobbs 2009).

While many forest restoration studies focus on establishing fast-growing tree species to unleash forest succession in such sites (Chazdon 2016; Lamb 2011; Montagnini and Finney 2011; Shono et al. 2007), less is known about the regeneration ecology of slow growing tree species such as most oaks (*Quercus* spp.). Oaks are key-stone species and provide a habitat for a vast number of epiphytic and understory plants. Furthermore, their massive acorn production serves as an important food source for most forest-dwelling granivores (eg. jays, squirrels, mice) and hereby indirectly regulate populations of higher predators such as foxes or pumas (McShea 2000). Oak forests also provide environmental products and services such as soil retention or aquifer recharge and are a prominent symbol in several cultures (Luna José 2003; Roy and Morgan 2011; Singh et al. 2016). For example, oak leaves appear on Mexico's national symbol and flag. However, many of these forests are currently fragmented and/or degraded (Abella et al. 2017; Ostfeld et al. 1996), while their natural regeneration in human modified landscapes is often so reduced that active restoration interventions are required to ensure their long term permanence (Ibáñez et al. 2017; Loftis and McGee 1993; McCreary 2009; Pérez-Izquierdo and Pulido 2014; Pons and Pausas 2006; Pulido 2002).

In seasonally dry oak forests, artificially introducing acorns or planting oak seedling usually ends up in very low establishment rates, mainly due to aridity and herbivory (González-Salvatierra et al. 2013; Leverkus et al. 2016; Rey Benayas et al. 2015). Several strategies have been tested with varying degrees of success to improve seedling survival, including transplanting seedlings beneath nurse shrubs (Rousset and Lepart 2000; Badano et al. 2009) or artificial shade structures (González-Salvatierra et al. 2013), covering the soil with leaf litter to increase water retention (Rousset and Lepart 2000; Tripathi and Khan 1990) or excluding animals that consume seeds and seedlings (Badano et al. 2015; Leverkus et al. 2016). One mechanism, that to our knowledge has not been tested yet, is topsoil translocation. This method implies moving the superficial soil layer from well-preserved sites (donor-sites) to target sites to be restored (receiver-sites). Along with soil, receiver-sites are inoculated with important ecosystem components such as soil nutrients, organic matter, micro-biota (Rivera et al. 2014) and plant propagules belonging to the old-growth vegetal community of the donor-site (Ferreira et al. 2015; Rokich et al. 2000). Topsoil translocation has been used to promote vegetation recovery on abandoned mining sites and quarries (Le Stradic et al. 2016), degraded riparian habitats (Van Looy 2011), impaired grasslands (Kiehl et al. 2010b), Mediterranean road fills resulting from infrastructure building (Rivera et al. 2014), savannas (Ferreira and Vieira 2017), wetlands (Munro 1991), meadows (Kiehl et al. 2010a), temperate woodlands (Craig et al. 2015), heathlands (Pywell et al. 2011) and has even been proposed to mitigate climate change (Boyer et al. 2016). This strategy may be particularly suited to enhance tree seedling establishment in ecosystems with slow soil formation processes, as occurs in seasonally dry oak forest from arid and sub-humid climates.

Moreover, moving forest topsoil has some important caveats. Geophytes and below-ground vegetative propagules can be destroyed during translocation (Craig and Buckley 2013), while donor sites may suffer more damage than can be auto-repaired. Undesired soil pathogens that inhabit mature ecosystems can be introduced into receiver sites (Ramos-Palacios and Badano 2014); furthermore, translocating topsoil for large scale projects can be expensive. Finally, much is yet to be scrutinized regarding best practices for enhancing tree seedling establishment using this technique. Different factors such as soil depth, transport and tillage procedures, loose-tipping and translocation moment may have varying effects on ecosystem restoration (Dickie et al. 2004; Howell and MacKenzie 2017; Rokich et al. 2000). Studying the effectiveness of topsoil translocation is therefore still required.

In this study, we assess topsoil translocation for restoring man-made clearings in seasonally dry oak woodlands in San Luis Potosí, Mexico. We addressed the following questions: (1) How does forest topsoil translocation alter micro-environmental conditions in clearings? (2) Does this improve oak seedling establishment in clearings? And, (3) does the additional translocation of leaf litter influence oak recruitment in clearings? As soil moisture is a crucial factor for oak establishment in seasonally dry forest (Badano et al. 2009), we propose that increased soil water retention of forest topsoil enhances seedling establishment.

2. Methods

2.1. Study area

This study took place in a disturbed oak forest within the Protected Natural Area, "Parque Nacional el Potosí", located in the state of San Luis Potosí, Central Mexico (21°54'46.4"N y 100°21'37.9"W, 1773 masl). The mean annual temperature is 16.3 °C and annual precipitation averages 732.9 mm with a rainy season between June and November (> 100 mm per month) followed by a prolonged dry season (< 20 mm per month) (Fernández-Eguiarte et al. 2012). Forest soils are calcareous and shallow (Vargas-Márquez 1984), covered by an humus-rich topsoil (15–20 cm depth) and a thick layer (> 30 cm) of decomposing leaf litter. Dominant oak species within the forest of our study site are *Quercus eduardii* Trel. *Quercus viminea* Trel. and *Quercus resinosa* Liebm. The clearings have compacted weathered soils with little organic matter, high rain water run-off and emerging bedrock (*Tepetate* in local Spanish). Vegetation in these clearings is scarce, or even non-existent.

2.2. Experimental design

We selected an eroded clearing adjacent to a forest patch to establish two independent randomized block designs. Both sites were located on a 10–15° slope facing the North and sharing the same bedrock. The

Table 1

Physic-chemical properties of forest and weathered soil at the El Potosí experimental site. P: Phosphor, NH_4: ammonium, NO_3: ammonium nitrates, Na: sodium, K: Potassium, Ca: calcium, Mg: magnesium.

Soil Sample	Soil Moisture (%)	Organic Matter (%)	pH	P (mg/Kg)	NH_4 (mg/Kg)	NO_3 (mg/Kg)	Exchangeable bases				Cation exchange capacity	
							Na (mg/Kg)	K (mg/Kg)	Ca (mg/Kg)	Mg (mg/Kg)	NH_4 (mg/Kg)	cmol (NH4/Kg)
Native forest topsoil	10	6	5.68	8.2	3.9	3.1	15.9	84.5	370.2	74.8	1043.7	5.8
Translocated semi-decomposed litter	24.5	41	6.75	32.5	14.7	35.9	36.2	227.8	1143.2	188.6	545.6	3
Translocated forest topsoil	10.4	8	7.11	18.3	3.6	4.8	39.7	107.8	700.4	121	1753.2	9.7
Native weathered soil	3.5	2.2	5.05	2.3	1.7	0.4	12.4	77	96	40.5	534.3	3
Translocated weathered soil	2.1	2.6	4.96	2.5	1.6	1.1	8	69.4	82.7	32.8	491.3	2.7