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Research article

# Facilitating the afforestation of Mediterranean polluted soils by nurse shrubs

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ABSTRACT

The revegetation of polluted sites and abandoned agricultural soils is critical to reduce soil losses and to control the spread of soil pollution in the Mediterranean region, which is currently exposed to the greatest soil erosion risk in Europe. However, events of massive plant mortality usually occur during the first years after planting, mainly due to the adverse conditions of high irradiance and drought stress. Here, we evaluated the usefulness of considering the positive plant–plant interactions (facilitation effect) in the afforestation of polluted agricultural sites, using pre-existing shrubs as nurse plants. We used nurse shrubs as planting microsites for acorns of *Quercus ilex* (Holm oak) along a gradient of soil pollution in southwestern Spain, and monitored seedling growth, survival, and chemical composition during three consecutive years. Seedling survival greatly increased (from 20% to more than 50%) when acorns were sown under shrub, in comparison to the open, unprotected matrix. Facilitation of seedling growth by shrubs increased along the gradient of soil pollution, in agreement with the stress gradient hypothesis that predicts higher intensity of the facilitation effects with increasing abiotic stress. Although the accumulation of trace elements in seedling leaves was higher underneath shrub, the shading conditions provided by the shrub canopy allowed seedlings to cope with the toxicity provoked by the concurrence of low pH and high trace element concentrations in the most polluted sites. Our results show that the use of shrubs as nurse plants is a promising tool for the cost-effective afforestation of polluted lands under Mediterranean conditions.



## 1. Introduction

The revegetation of degraded sites and abandoned agricultural soils is critical to reduce soil losses in the Mediterranean region, which is currently exposed to the greatest soil erosion risk in Europe (Grimm et al., 2002; Panagos et al., 2015). Among degraded sites, the revegetation of polluted sites should be prioritised, as the increase in soil erosion could lead to the spread of pollutants from polluted spots. However, establishing a woody plant cover in these degraded sites is a challenging task, given that the environmental conditions in these sites are, in general, far from similar to those in which natural regeneration occurs.

In barren polluted sites, such as those affected by mining activities, vegetation is often poorly developed and the soil surface is exposed to high irradiance; soils are usually poor in organic matter, and their structure is frequently altered (Tordoff et al., 2000; Walker, 2002), leading to a decreased water holding capacity (Stocking and Murnaghan, 2001). All these factors strongly reduce seedling survival during the dry season, which constitutes one of the most limiting demographic processes for regeneration in Mediterranean woody plant species (Pérez-Ramos et al., 2012; Pulido and Díaz, 2005; Rey and Alcántara, 2000). Consequently, mortality rates during the first years after planting are usually very high in Mediterranean degraded sites (Gomez-Aparicio et al., 2004; Navarro-Cerrillo et al., 2005; Pausas et al., 2004), and the afforestation of large degraded areas poses a huge cost for local and regional authorities.

The need for alternative afforestation techniques prompted a number of studies during the last decade to explore the potential application of positive plant–plant interactions for the restoration of degraded sites (Castro et al., 2004; Gomez-Aparicio et al., 2004; Maestre et al., 2001). Based on results obtained in these studies, many authors have called for a change in the paradigms of traditional afforestation techniques towards a new conceptual framework that considers the spatial heterogeneity of vegetation structure and promotes these positive plant–plant interactions

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(Gómez-Aparicio, 2009; Padilla and Pugnaire, 2006; Rey-Benayas et al., 2008). Many studies in Mediterranean ecosystems have reported that the presence of pioneer shrub species (often called nurse plants) facilitates the establishment of other late-successional species under their canopies, mainly due to the amelioration of extreme temperature conditions and the improvement of plant water status (Callaway, 1992; Castro et al., 2004; Gómez-Aparicio et al., 2005; Padilla and Pugnaire, 2009), but also by the concurrence of better soil conditions under the shrubs (Pugnaire, 1996). In addition, facilitation by nurse plants may also be mediated by indirect underlying mechanisms when the nurse species promotes other mutualistic or beneficial interactions with soil microorganisms, such mycorrhizal species (Goberna et al., 2007; Gonzalez-Polo and Austin, 2009; Duponnois et al., 2011; Martínez-García et al., 2011). The target species may also benefit from the release of herb competition for water and nutrients under the nurse shrubs (Cuesta et al., 2010).

Positive plant–plant interactions are expected to be especially beneficial under high abiotic stress (Callaway et al., 2002; Lortie and Callaway, 2006), and therefore the application of the facilitation effect could be particularly useful in highly disturbed environments (Brooker et al., 2008; Pueyo et al., 2009; Zvereva and Kozlov, 2007). Surprisingly, there are very few examples of the application of these techniques in the restoration of polluted sites. In these sites, the presence of nurse shrubs might have additional benefits to the target species, given that the higher levels of soil organic matter detected under the shrub canopy (Ginocchio et al., 2004) as well as the stabilisation of pollutants in the nurse root system (Domínguez et al., 2009; Frèrot et al., 2006) could reduce the levels of bioavailability of some pollutants. Conversely, airborne pollutants can be captured and accumulated more intensively under the shrub canopy than in open gaps, resulting in a better performance of the target species at a certain distance from the shrub canopy (Eränen and Kozlov, 2007). To date, very few studies have assessed the role of the chemical stress (i.e. high concentrations of toxic elements in the soils) in the intensity of the facilitation by shrubs. According to the abiotic stress gradient hypothesis (Bertness and Callaway, 1994; Callaway et al., 2002; Pugnaire and Luque, 2001), the intensity of the facilitation effect enhances with increasing stress. Therefore, given similar levels of water and light conditions, it would be expected that the facilitation effect provided by shrubs will be higher as the chemical stress (i.e. soil pollution) increases. Here, we aimed to test this hypothesis.

In this study, we evaluated the effectiveness of using nurse shrubs as planting microsites for acorns of *Quercus ilex* (Holm oak) along a gradient of soil pollution in the Guadiamar River Valley (southwestern Spain). Soils in this area were affected by a mining accident that polluted them with trace elements, mainly As, Cd, Cu, Pb, and Zn (Domínguez et al., 2008). We followed a two-phase restoration strategy, first selecting shrubs that were planted during the initial afforestation of the area (after the accident), and secondly, planting acorns under the shrubs as potential facilitators of oak recruitment. This multi-phase technique, which attempts to mimic the natural sequence of the successional process (i.e. herb-shrub-tree), could result in a valuable restoration tool of degraded areas, as previously proposed for other Mediterranean non-polluted forests (Gomez-Aparicio et al., 2004; Siles et al., 2008). Specifically, we were interested in testing that: 1) the presence of shrubs have a significant effect on soil properties, particularly organic matter, pH, and nutrient content, which results in a better nutritional status of the target plant and in a lower accumulation of trace elements in the aboveground biomass; 2) microsites under shrubs are more favourable for emergence, survival, and growth of oak seedlings than the open, unprotected microsites; 3) the intensity of facilitation increases along a gradient of soil pollution (chemical stress). As a secondary objective, we aimed to test whether the intensity of the facilitation is higher when a pioneer shrub species (*Retama sphaerocarpa*), rather than a late-successional shrub (*Phillyrea angustifolia*), is used as a nurse in these harsh environments. Understanding the effectiveness of different nurse plants constitutes an issue of major interest for the conservation and restoration of degraded ecosystems (Gómez-Aparicio, 2009; Rolo et al., 2013).

## 2. Material and methods

### 2.1. Study site and species

The Guadiamar River Valley is located in southwestern Spain. The climate is Mediterranean-type with an annual average of about 2900 h of sunshine and maximum values of solar radiation exceeding 1000 W $m^{-2}$. The average annual temperature is 19 °C, the average annual rainfall is 610 mm, and potential evapotranspiration is 774 mm.

The area was affected by a large mining accident in 1998 that contaminated the soils, mostly under agricultural production, with As, Cd, Cu, Pb, Tl, and Zn (Cabrera et al., 1999; Garralón et al., 1999). Although sludge and contaminated topsoils were removed after the accident, the underlying soils still contained high concentrations of trace elements (Moreno et al., 2001). In 1999–2001 the affected area was afforested using native Mediterranean shrub and tree species as part of a large soil remediation and phytomanagement programme (Domínguez et al., 2008). Plantations followed the traditional technique using regular planting grids, with densities ranging from 480 to 980 plants per hectare. The success of these plantations was very irregular; plant species in the higher terraces showed higher mortality rates, which was positively related to the drought stress and the high levels of soil pollution, while riparian species showed the highest survival and growth rates (Domínguez et al., 2010a). A monitoring survey carried out eight years after the plantations showed that shrub species contributed the highest percentage of cover (Rodríguez et al., 2009).

We selected Holm oak (*Q. ilex* subsp. *ballota* Desf. Samp), which is the most common late-successional tree in the native forests in the area, as the target species to afforest. We tested the potential of two of the most common shrub species planted in the area as nurse plants for the establishment of Holm oak seedlings: *R. sphaerocarpa* and *P. angustifolia*. In one of the experimental sites where *P. angustifolia* was absent (Site 2, see below), wild olive saplings (*Olea europaea*) of similar age and height were used instead as late-successional nurse plants.

### 2.2. Experimental design

Four sites were selected along a gradient of soil pollution in the Guadiamar Valley, determined by the distance to the pollution source, based on previous surveys of the spatial distribution of soil and plant trace elements along the Valley (Domínguez et al., 2008). All these sites were under agricultural or pasture production before the accident (1998), and were afforested between 1999 and 2001 during the implementation of the remediation programme.

Holm oak acorns were collected in October–December 2005 from native, non-contaminated forests in the Valley. Unhealthy acorns were discarded using the flotation method (Gribko and Jones, 1995), and the rest of the acorns were stored at 2–4 °C until used. In December 2005 the selected acorns were sown in 15 experimental units per site. Each experimental unit consisted of a pair of planting microsites, separated by a maximum distance of 10 m: a) SHRUB, under the canopy of the selected shrub species, and b) OPEN, in the open sites, without the protection of any plant