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Assessment of revegetation of an acidic metal(loid)-polluted soils six years after the incorporation of lime with and without compost

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ABSTRACT

The process of passive revegetation of chemically degraded soils through assisted remediation was assessed under field conditions 6 years after amendment application. In 2009, three treatments were applied: unamended soil (untreated), soil amended with lime, and soil amended with lime + compost. For each field plot, main soil physico-chemical characteristics were determined (pH, organic matter, moisture content at field capacity and exchangeable Cu), while plant colonist development was assessed (plant cover and aboveground biomass). The same evaluation was carried out in 2015. A single application of amendments maintains a neutral pH after 6 years. Thus, neutralization of the soil acidity was stable over time. In 2009, lime + compost was the best treatment for increasing the plant cover. Although the soil organic matter content decreases in year 6, plant cover remained stable over time in this treatment. Incorporation of both organic matter and lime was pivotal at the beginning of the revegetation process, allowing the creation of a potentially self-sustaining ecosystem. No maintenance and/or additional application of amendments was required. Aboveground biomass showed differences between years, possibly explained by changes in climate conditions between 2009 and 2015, and/or changes in nutritional conditions (soil fertility) and plant competition. Plant biodiversity in year 6 was similar for all treatments. The long-term results of plant cover show lime and specially lime + compost as promising amendments to revegetate polluted soils of the Puchuncaví Valley.

1. Introduction

Environmental problems associated with the operation of metal (loid) smelters are a global concern (Ettler, 2016). This is the case of the biodiversity-rich coastal Mediterranean ecosystem of the Puchuncaví valley in central Chile, that was exposed to atmospheric depositions of sulphur dioxide (SO_2) and metal(loid)-rich particles from the Ventanas Industrial Complex, composed by a copper smelter and a thermal power plant from 1964 to 1992 (Folchi, 2006). During this period, soils surrounding the industrial complex accumulated metal(loid) at high concentrations, and were acidified and strongly eroded, as a result of the loss of the native sclerophyllous vegetation cover (De Gregori et al., 2003; Ginocchio, 2000; Neaman et al., 2009). The loss of native vegetation could lead to further environmental problems related to pollution. For example, it could increase metal(loid) leaching and/or the resuspension of as a result of the metal-rich dust, possibly resulting in their ingestion by local population (Bierkens et al., 2011; Tordoff et al., 2000). As a result, revegetation is one option for reducing environmental risks associated to acidic and metal-polluted soils.

Revegetation of chemically degraded areas has been evaluated using various processes including natural attenuation, which takes long time, and assisted revegetation by adding cost-effective and minimally invasive soil amendments reducing the recovery time of the plant cover (Adriano et al., 2004; Mench et al., 2006). In the last case, two options have been used for restoring plant cover once plant-growth restrictions have been removed/reduced from the site. The first is active revegetation, with seeding and/or transplanting of plant species (Alvarenga et al., 2008; Clemente et al., 2005). The second is passive revegetation, with development of plant colonists from the soil seed bank, seeds dispersed by natural vectors, and/or regeneration of remaining plants (Álvarez et al., 2003; Conesa et al., 2007). Córdova et al. (2011) previously showed that plant cover and aboveground biomass were similar under active and passive revegetation regimes, in the Puchuncaví valley suggesting that plant cultivation was unnecessary for

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ecological rehabilitation (see, however Van Andel and Aronsonn, 2012). It was concluded that the soil seed bank (including both seeds from native and exotic species) of the site was sufficient to recover plant cover and biomass production partially similar to original vegetation, after application of proper soil amendments.

Lime and organic matter are two amendments that are commonly used for revegetation of chemically degraded soils (e.g. Bes and Mench, 2008; Gray et al., 2006; Solís-Dominguez et al., 2012; Yan-Bing et al., 2017). Lime can reduce metal bioavailability in contaminated soils, based on either newly-formed solid phases (metal precipitation or co-precipitation) or on reactions with the surface of existing particles (e.g. metal adsorption) (Ma et al., 2006; McBride, 1994). On the other hand, organic amendments can provide essential nutrients (such as N and P), increase water holding capacity and sorb metals (Tordoff et al., 2000; USEPA, 2007), which is pivotal for degraded soils, such as those of the Puchuncaví valley (Ginocchio, 2000).

Although there are field studies on the effectiveness of lime and organic matter for processes of aided soil remediation (Mench et al., 2006; Quintela-Sabaris et al., 2017 and references therein), there are few long-term assessments evaluating passive revegetation from the remaining seed soil bank and these studies have been conducted in one or two seasons. Therefore, we lack information on the long-term effectiveness of the revegetation process after applications of amendments in polluted soils. In most cases there is little certainty on whether revegetation is long term maintained after a single amendment application and if the seed soil bank is enough to initiate the ecosystem functions. In particular, soil reacidification and biodegradation of the organic matter can increase metal solubility to ante-remediation levels (Bolan et al., 2014; Hamon et al., 2002; Stehliková et al., 2016). Long-term field experiments would identify any changes in soil properties caused by soil management practices and would allow assessment of the positive and negative influences (Stehliková et al., 2016).

Based on Córdova et al. (2011), reporting that amendments can increase plant cover and biomass in the short term, the following questions arise: Are these effects stable over time? And do the amendments require maintenance and/or additional applications? Hence, this study aims to reassess soil physico-chemical characteristics, plant cover and aboveground biomass 6 years after initial soil amendment.

2. Materials and methods

2.1. Study area

This study focused on the same field trial set up by Córdova et al. (2011). A single application of amendments (lime with and without compost) was carried out in 2009, and this assessment took place six years after amendment application (2015). This study only considered the plots used for the passive revegetation regime (see Córdova et al., 2011 for more details).

The trial is located at Los Maitenes (1 km southeast of the Ventanas Industrial Complex) (UTM coordinates: H19S 268,537 E 6,371,904 N), an area with high total soil Cu, Pb, Zn, Cd and As, and low soil pH values of the Puchuncaví Valley, Chile (Ginocchio, 2000; Ginocchio et al., 2004; González et al., 2014). High total soil Cu (up to 680 mg Cu kg^{-1} soil) and low soil pH (in KNO_3: 3.9–5.9) led to high Cu bioavailability (Neaman et al., 2009). Verdejo et al. (2015a, 2015b) reported that Cu is the metal of concern in the study area in terms of plant growth. Sandy soils in Los Maitenes also have lower organic carbon and nitrogen contents than soils located further away from the smelter, restricting plant growth further (Ginocchio, 2000).

2.2. Experimental design

Three treatments were assessed under the passive revegetation regime described in Córdova et al. (2011): (1) Untreated (UNT), (2) soil amended with lime (L), and (3) soil amended with lime + compost (LCO). Each treatment was assessed in three plots of 24 m^2 (6 m × 4 m). Calcium hydroxide ($Ca(OH)_2$) was applied at a rate of 3 g kg^{-1} soil (6.7 t ha^{-1}) in L and LCO treatments. Compost was applied at 60 g kg^{-1} soil (133 t ha^{-1}) only for the LCO treatment. The amendments were applied in March 2009 and the soil was ploughed to a depth of 15 cm (UNT soils were also ploughed). In 2009, plots were irrigated as described in Córdova et al. (2011). From 2010 onwards, the plots were not irrigated and neither maintained by perimeter fence.

2.3. Soil and revegetation assessment

In Córdova et al. (2011), soil samples were taken and plant cover and aboveground biomass were determined in spring 2009. For this study, the same procedures were carried out in spring of 2015. See Córdova et al. (2011) for more details.

In addition to analyses done in Córdova et al. (2011) in year 1, plant relative abundance and shoot Cu concentration were measured in year 6. Plant relative abundance was determined as the relative contribution of different species to plant cover in a 25-point grid (0.11 m × 0.11 m). On the other hand, Cu concentration was determined only in the aboveground parts of the dominant plants found in our field trial, i.e., the exotic species *Lolium perenne* and *Eschscholzia californica*. The analysis was performed by flame atomic absorption spectroscopy using standard methods (Sadzawka et al., 2007).

2.4. Statistical analysis

Analysis of variance (ANOVA) for randomized blocks was used to compare the effects of amendments on the soil physico-chemical characteristics, for the same year; statistically significant differences were determined using a Tukey test. Student's *t*-test for randomized blocks was used to compare the effects of years on the soil properties, for the same treatment. The analyses were carried out using Minitab 17.

For plant cover, due to the nature of the data (expressed as percentage), the most appropriate model for this analysis was the fractional response regression model with logit (Ferrari and Cribari-Neto, 2004; Papke and Wooldridge, 2008). Mean comparison was carried out as pairwise comparison of marginal means. The analysis was carried out using Stata 14.0.

Aboveground biomass dataset was analysed with a generalized linear model (GLM) for log normal distribution (Hardin and Hilbe, 2012). The mean comparison was carried out as pairwise comparison of marginal means. For comparison between years for the same treatment, the analysis was carried as unbalanced. The analysis was carried out using Stata 14.0.

Plant composition among treatments and years were compared using a cluster analysis through the unweighted pair group method with arithmetic mean (Sneath and Sokal, 1975). For this purpose, a distance matrix for the presence or absence of species was estimated through the Jaccard index (Wolda, 1981). Significance of the cluster was obtained using 1000 Montecarlo simulations of the distance matrix to find a critical value (Jaksic and Medel, 1990). The analysis was carried out using "pvclust" library in R software (R Development Core Team, 2016).

3. Results and discussion

3.1. Evaluation of soil properties in year 6

The effect of treatments and time on soil physico-chemical properties is shown in Table 1. The pH of the L and LCO soils slightly decreased, possibly due to rhizosphere activity of vegetation (Jones et al., 2004), mineralization of organic matter, atmospheric deposition, and/or leaching of base cations in these sandy soils. Although, pH was maintained circumneutral. These results are similar to those of Madejón