Three-year study of fast-growing trees in degraded soils amended with composts: effects on soil fertility and productivity

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Abstract

Currently, worries about the effects of intensive plantations on long-term nutrient supply and a loss of productivity have risen. In this study two composts were added to degraded soils where this type of intensive crops were growing, to avoid the soil fertility decrease and try to increase biomass production. For the experiment, two degraded soils in terms of low organic carbon content and low pH were selected in South-West Spain: La Rábida (RA) and Villablanca (VI) sites. Both study sites were divided into 24 plots. In RA, half of the plots were planted with Populus x canadensis “I-214”; the other half was planted with Eucalyptus globulus. At the VI site, half of the plots were planted with Paulownia fortunei, and the other plots were planted with Eucalyptus globulus. For each tree and site, three treatments were established (two organic composts and a control without compost), with four replications per treatment. The organic amendments were “alperujo” compost, AC, a solid by-product from the extraction of olive oil, and
BC, biosolid compost. During the three years of experimentation, samples of soils and plants were analyzed for studying chemical and biochemical properties of soil, plant growth and plant nutritional status and biomass production. The composts increased total organic carbon, water-soluble carbon, nutrients and pH of soil only in acidic soil. Soil biochemical quality was calculated with the geometric mean of the enzymatic activities (Dehydrogenase, β-glucosidase, Phosphatase and Urease activities) determined in soils. The results showed a beneficial improvement in comparison with soils without compost. However, the best results were found in the growth and biomass production of the studied trees, especially in *Eucalyptus*. Nutritional levels of leaves of the trees were, in general, in the normal established range for each species, although no clear effect of the composts was observed. The results of this study justify the addition of compost to guarantee good biomass production and maintain or improve soil management in degraded soils, especially in acid soils.

Keywords: *Populus x canadensis*, *Paulownia fortunei*, *Eucalyptus globulus*, enzymatic activities, nutrients

1. Introduction

Biomass of trees is one of the main sources of energy and is currently the most important supply of renewable energy in the world (Lauri et al., 2014). By 2050, FAO (2001) infers that these plantations will cover 5–10% of the world's forested land area; therefore, their effects on the environment, and in particular on soil, have to be studied.

From the environmental point of view, fast-growing tree biomass production replaces non-renewable carbon materials and promotes carbon sequestration and other ecosystem services such as improvement of soil and water quality, reduced erosion and increased biodiversity (Evangelou et al., 2012). Moreover, the proportion of biomass plantations
could be considered part of the global strategy for enhancing rural development and
could reduce the net atmospheric accumulation of CO$_2$ (García Morote et al., 2014).
However, worries about the effects of these intensive plantations on long-term nutrient
supply and loss of productivity of soils have arisen (Vanguarda and Pitman, 2009). In
particular, in the Mediterranean region, the increasing pressure on agricultural land can
result in high nutrient loss and declines in soil fertility (Cuvardic et al., 2004). These
soils are often deficient in organic matter, nitrogen, and phosphorus (Rashid and Ryan,
2004) causing decreases in nutrient supply and, in turn, direct effects on plant
productivity. In these types of degraded areas, soils present weakened ecosystems with
low organic matter and nutrient content, which are prone to irremediable degradation

One method for recovering degraded soils is to incorporate organic matter from
organic waste (Pascual et al., 1998). These organic materials can improve microbial
activity and growth, enhancing biogeochemical nutrient cycle (Ros et al., 2003;
Lakhadar et al., 2011). Moreover, the application of organic wastes with a high quality
to soils can reduce the environmental impact associated with waste disposal and
enhance the productivity of biomass production systems (Quaye et al., 2011). This study
is an advance in using organic wastes in degraded soils. The addition of compost from
organic material easily available and inexpensive, is an interesting option to improve
not only soil fertility, but also to increase the value of these soils for fast biomass crops,
increasing plant nutrition and yield.

The aim of this three-year-study was to evaluate (at short and midterm) the influence
of two stable composts on chemical and biochemical productivity of two soils planted
with three common fast growing trees: a hybrid of *Populus nigra* and *Populus deltoids,*
Eucalyptus globulus and Paulownia fortunei. We hypothesize that composts could improve soil quality and, therefore, increase biomass production in on degraded soils.

2. Materials and methods

2.1 Study site and experimental design

Two degraded soils were selected in the province of Huelva (Andalucía, South-West Spain). One was located at the University of Huelva, Campus of La Rábida (RA) (UTM, zone 29S, X: 684875, Y: 4119130, 15 m.a.s.l.); the other degraded area was located in the area of Villablanca town (VI), (UTM, zone 29S, X: 649340, Y: 4132898, 129 m.a.s.l.). The main soil characteristics are showed in Table 1.

<table>
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<tr>
<th>TABLE 1</th>
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<tr>
<td>The total area of each site was 720 m². Both study sites were divided into 24 plots (30 m² per plot). In RA, half of the plots (12) were planted with Populus x canadensis “I-214”, which is a hybrid of Populus nigra and Populus deltoides (PO). The other 12 plots were planted with Eucalyptus globulus “O-ENCE” (E). In VI, half of the plots (12) were planted with Paulownia fortunei “Pw-UHU” (PA), and the other 12 plots were planted with Eucalyptus globulus “O-ENCE” (E). In each plot, 15 plants of the corresponding crop were established. At the time of planting (between April and June 2011), the vegetative material consisted of Eucalyptus plants of 25 cm in height coming from rooted softwood cuttings, Paulownia plants of 15–20 cm in height coming from rooted and sprouted root cuttings, and poplar hardwood cuttings of 20 cm in length. For each plant species and site, three treatments were established (two organic composts and a control without a compost addition), with four replications per treatment. The organic amendments were: alperujo compost, AC, a solid by-product from the extraction of olive oil provided by the company “Coto Bajo” Córdoba Southern Spain, and biosolid compost, BC, provided by EMASESA, Sevilla, Southern Spain, constituted of...</td>
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wastewater sludge from a water treatment plant and green waste from parks and
gardens. The main characteristics of the two comports are shown in Table 2. The
compost application was done in November 2011 around each tree in the following
doses: four kg of Alperujo Compost in AC plots and 2.25 kg of Biosolid Compost in BC
plots. The doses were equivalent to 300 kg of N per ha. The same compost application
was done in the same plots in November 2012. Each year, from May to September and
according to the rainfall, 250–350 mm of water was provided by drip irrigation in order
to offset summer drought at both sites.

TABLE 2

2.2 Soil and leaves samples

Three soil samplings were performed in both sites in spring of 2012 (first sampling),
spring of 2013 (second sampling) and spring 2014 (third sampling). Soil samples were
taken around the trees at 0-20cm depth. The soil was sieved (2 mm) and one sub-sample
was stored at 4 °C for a few days to prevent moisture loss before assaying for
microbiological analysis. The other sub-sample was air dried, crushed and sieved (<2
mm and <60µm) for chemical analysis.

At each plot a representative sample of leaves of each tree was collected at the same
time than soil samples. Vegetal material (leaves) was washed with a 0.1N HCl solution
for 15 s and with distilled water then for 10 s. Washed samples were oven dried at 70
°C. Dried plant material was ground and passed through a 500-µm stainless-steel sieve
prior to preparation for analysis.

2.3 Shoot growth and biomass production
Crop development was followed through periodic measurements of height (H) and stem diameter at the base (D), measured 7 cm above ground). This is every three months, three trees per plot were measured for height (H) and 5 trees per plot were measured for diameter (D).

Part of biomass assessment was carried out by cuttings and direct weighing (39 trees of Populus, 28 trees for Eucalyptus and 12 for Paulownia). These measures were carried out at different seasons and years to weigh different sizes of trees. The other part of the biomass assessment was done using allometric equations which relate the diameter at the base and/or the height of the main stem with the aboveground dry biomass (Pannacci et al., 2009; Paris et al., 2011; Bouvet et al., 2013).

The equations for the three-year experiment to calculate the tree biomass were determined by removing different plants of each species (Table 3). Each plant was separated into leaves and woody biomass. Then, material was dried, and dry weight was recorded. Total dry biomass per plant was calculated as the sum of both parts. Ten models of allometric equations depended on D and H; the combination of D and H were tested. Table 3 shows the best equations fitting.

### TABLE 3

| 2.3 Chemical and biochemical analysis in soils and plants |

Soil pH was measured in a 1M KCl extract (1:2.5, m/v) after shaking for one hour (Hesse, 1971) using a pH meter (CRISON micro pH 2002). Total organic carbon (TOC) was determined by dichromate oxidation and titration with ferrous ammonium sulphate according to Walkley and Black (1934) and total Kjeldahl-N (TKN) by the method described by Hesse (1971). Water-soluble carbon (WSC) content was determined using a TOC-VE Shimadzu analyser after extraction with water using a sample-to-extractant ratio of 1:10. Available-P was determined by extraction with
sodium bicarbonate at pH 8.5 (Olsen et al., 1954), and available-K was determined after
extraction with ammonium acetate at pH 7.5 (Dewis and Freitas, 1970).

Dehydrogenase activity was determined by the method of Trevors (1984). β-
glucosidase activity was measured as indicated by Tabatabai (1982). Phosphatase
activity was measured by the method proposed by Tabatabai and Bremmer (1969).
Urease activity was determined according the method proposed by Kandeler and Geber
(1988) and modified by Kandeler et al. (1999).

All enzyme activities were expressed in $\mu$g PNP g dry soil$^{-1}$ h$^{-1}$ (PNP, p-
nitrophenol), except dehydrogenase activity, which was expressed in $\mu$g INTF g dry
soil$^{-1}$ h$^{-1}$ (INTF, p-iodonitrotetrazolium formazan) and urease activity, which was
expressed in $\mu$g N-NH$_4^+$ g dry soil$^{-1}$ h$^{-1}$.

Pseudo-total trace element concentrations in soil samples (< 60 μm) were
determined by digestion with aqua regia (1:3 v:v conc. HNO$_3$:HCl) in a microwave
oven (Microwave Laboratory Station Mileston ETHOS 900, Milestone s.r.l., Sorisole,
Italy). The term pseudo-total accounts for the aqua regia digestion, because it does not
completely destroy silicates. Trace elements in all the extracts were determined by ICP-
OES (inductively coupled plasma-optical emission spectrometry) using a Varian ICP
720-ES (simultaneous ICP-OES with axially viewed plasma).

Plant material was analysed for total N by Kjeldahl digestion (Hesse, 1971).
Macronutrients (P, K, S, Ca and Mg) and micronutrients (Cu, Mn and Zn) were
extracted by wet oxidation with concentrated HNO$_3$ (65%, trace analysis grade) under
pressure in a microwave oven. Determination of macronutrients and microelements in
the extracts was performed by ICP-OES. The accuracy of the analytical methods was
assessed through BCR analysis (Community Bureau of Reference) of a plant sample
(INCT-OBTL-5, Oriental Basma Tobacco leaves).
2.5. Soil quality and statistical analysis

Soil quality index was calculated according to Paz-Ferreiro et al. (2012). The geometric mean (a general index to integrate information from variables that possess different units and range of variation) of the assayed enzyme activities was calculated for each sample as:

\[ \text{GM} = (\text{Dehydrogenase} \times \beta-\text{glucosidase} \times \text{Phosphatase} \times \text{Urease})^{1/4} \]

All statistical analyses were carried out with the program SPSS 20.0 for Windows. Results of each soil and tree species were analyzed with ANOVAs, considering treatment as the independent variable. Significant statistical differences of variables between treatments were established by Tukey’ test (p < 0.05). Data normality was tested prior to analysis, and, when necessary, variables were transformed logarithmically, and normality was then passed in all cases.

3. Results and discussion

3.1. pH, TOC, WSC and nutrients in soil

Addition of compost did not cause any significant change in pH values in RA soils (Figure 1a). However, due to the acidic nature of the VI soil (Table 1), composts (especially AC, Table 2) increased pH values and the differences were significant in some cases (Figure 1d). In general, maximum values of pH were observed in both soils in 2013 after the second addition of the amendments. In the third sampling, a slight increase in the acidity was observed, probably caused by the mineralization of the organic matter that could cause proton release in the soil (Naramabuye and Haynes, 2006).

FIGURE 1
The effect due to plant growth on pH (excluding the amendment effect) can be observed in the treatment without compost addition. Poplar growth did not change pH in soil during the three years of the study. Similar results were found by Ciadamidaro et al. (2013, 2014a) when studying *Populus alba* in degraded soils. In the case of *Eucalyptus* in RA soil, trees increased pH values (Figure 1a), although similar behavior was not observed in VI soil (Figure 1d). It is known that Eucalyptus could decrease the pH in soil (Roades and Binkle, 1996); although, in this study, this result was not observed (in all treatments). Perhaps, to observe this effect clearly, more years of study are needed. Finally, in the case of *Paulownia*, pH values slightly decreased in the last sampling. Madejón et al. (2014) found similar results for this plant when it was growing in a neutral soil.

The main objective of the compost addition was to increase TOC contents and, consequently, soil quality (Table 1) (Hazleton and Murphy, 2007). Organic matter is essential in soil to maintain its fertility (Stevenson, 1982) and to assure the healthy growth of the trees. In fact, in treated soils, an increment in TOC was observed compared with the soils without amendments, with significant differences in some cases (Figures 1 b, d). Between the two studied composts, AC showed better results in time, although the efficiency of this parameter was quite similar for both amendments.

In *Populus* soils, TOC increased in time (Figure 1b), and in *Eucalyptus* soils, TOC increased in time at both sites, especially in VI (initial concentrations of TOC were lower than in RA; Figures 1 b, e). However, in soils without compost, a decrease in TOC was observed, although values increased in the last sampling compared with the 2013 sampling, which was likely due to the input of plant litter and root exudates (Ciadamidaro et al., 2014a). Similar behavior was observed in *Paulownia* soil without
amendment (Figure 1e). Amended soils under Paulownia reached maximum values in 2013, after the second amendment addition.

Water-soluble Carbon (WSC) was also positively influenced by compost addition in both soils and, for the three tree species, the maximum values were observed in 2014 (Figure 1c, f). This value was higher at the end of the study for all species and treatments. This is related to the fact that WSC originates mainly from the release of organic substances from fresh material during decomposition, thus contributing to soil nutrient cycling (Qualls et al., 1991).

In general, values of N, P and K in both experimental sites can be considered low (Hazelton and Murphy, 2007) (Table 1); therefore, the addition of compost was necessary to increase nutrients in soil, especially P and K. The composts increased content of N, although these values were still low, and significant differences were only observed in VI soil under Eucalyptus amended with AC (Figures 2a, d) with lower N content than in RA soils. As for the other studied parameters, AC was the amendment that, in general, caused the greatest increment in chemical fertility and the most effective in time (Figure 2). In RA soils, N concentrations were similar in time or even increased for the two species. In the VI site, Paulownia tended to increase soil’s N content in time. This slight increase could be related to the relatively high contents of N in leaves that turn to litter in the soil (Madejón et al., 2014). However, in the case of Eucalyptus soil, N concentrations decreased, maybe because of the N-poor Eucalyptus litter (Ngao et al., 2009).

FIGURE 2

Availability of P and K were significantly improved by both amendments (Figures 2c, d, e, f) and in both areas, especially in the last two years of the study (after two amendment additions). In particular, AC increased soil concentrations of P 2-fold.
In soils without compost, similar behavior was observed for P at both sites, and values tended to be lower at the end of the experiment compared with the initial values (Figure 2). Concentrations of available K were similar at both sites (Table 1); however, the addition of compost caused a bigger increment in RA soils (maximum of 400 mg kg\(^{-1}\) in AC treatment). This is related to the acidic nature of VI soil in which the availability of macronutrients is curtailed (Brady and Weil, 2002).

3.2 Enzymatic activities

The geometric mean (GM) was used as a way to summarize information from pools of all studied enzymatic activities (Figure S1). Thus, to get an overall indicator of changes in the general biochemical status of the soils, GMs were calculated. In general, GMs tended to be higher in amended soils, although significant differences were only observed in last samplings for *Eucalyptus* at both sites (Table 4). These data point out the relevance of the composts improving soil quality, especially in *Eucalyptus* soils.

Different studies have shown the beneficial effects of the application of organic amendments, such as alperujo compost (Kohler et al., 2008) or biosolid compost (Alguacil et al., 2009), on quality of degraded soil by increasing the proliferation and development of soil microorganisms. These effects are related to the enhancement of the soil enzyme activities, which are considered key factors contributing to soil activity, fertility and availability of nutrients to plants (Mengual et al., 2014).

**TABLE 4**

In the RA site, in soils under *Populus*, the best results were found in BC treatment; for *Eucalyptus* soils, no clear differences between both composts were observed. In soil without amendment, this biochemical index decreased by 48% at the end of the experiment in the case of *Eucalyptus*, and by 20% in the case of *Populus*. In the case of
Eucalyptus soils, a decrease was observed in time of GM in soils without composts, and a significant improvement in the biochemical status was observed in amended soils. These results remark the necessity of adding this type of low-cost residue to these crops due to the low nutrient concentrations in leaves of Eucalyptus trees; therefore, their annual litter input is also generally lower than deciduous trees (Populus and Paulownia) (Molinero and Pozo, 2004).

In the case of the VI site, a general tendency in reducing GM values in time was observed. In this soil, higher values were also found with the BC treatment, and no differences due to the different species (Paulownia and Eucalyptus) were found.

In RA soils in 2013 and VI soil in 2014, GM biochemical values were especially low, likely due to the low moisture of the soil in these samplings (data not shown) compared with the other samplings. In fact, the adequate water content in the soil is one of the most important factors affecting the soil microbiological and enzymatic processes (Gianfreda and Ruggiero, 2006).

Between the two sites, values of GMs were higher in VI soils. Despite its more acidic pH and lower chemical fertility (Table 1), VI soil presented a better initial biochemical status based on the values of the enzyme activity (Table 4). The lower biochemical status of RA soils could be related to their high content of copper (Table 5). World soil levels of Cu are 14 mg kg⁻¹ (Alloway, 2013), and the RA site presented this amount ten-fold. Although Cu is an essential element, its excessive availability in soil is potentially toxic to plants and microorganisms, and inhibits soil enzyme activities (Bååth, 1989).

### TABLE 5

<table>
<thead>
<tr>
<th>3.3 Plant growth and biomass</th>
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<tr>
<td>At the RA site, the mortality of the planted poplars accounted for 51.5% at the time of sampling in 2012, whereas all the eucalyptus trees were still alive. Therefore, the</td>
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assay was performed with 41.5% of those initially planted poplars. The reason for the high mortality of poplar trees could be attributed to the way they were planted (non-rooted cuttings), to an inadequate handling of cuttings or to the date of plantation. Once planted (pinned to the ground), they normally develop their root system before the shoot. However, the late planting date could cause the buds to open early and the aerial part of the plant to develop more rapidly due to the high temperature. In spite of the irrigation, the higher generated transpiration rate could not be supported by the poor root system, and the plants dried out. For the other two species all plants survived; 100% survival.

The effect of compost was evident in the biomass production of the different species. The highest cumulative growths were always found in soils with compost (Figure 3). In RA soil for this species, BC was seen as the most effective treatment for increasing biomass since August 2012 (Figure 3a). However, AC did not cause an important difference with non-amended soil. In the case of Eucalyptus in the same soil, similar results with BC were found, although differences were not as evident, as in the case of poplar (Figure 3 b). In VI soils (with a lower level of fertility than RA soils) (Figures 1 and 2), the addition of amendments increased the cumulative growth of both species. In the case of Paulownia, the effect was clear after June 2013, while, in Eucalyptus, this effect was evident since the beginning of the measures, showing better results with BC.

RESULTS

Results of total biomass production at each site are in Table 6. The highest poplar biomass production was observed in BC treatment, showing an average total dry biomass (TMD) of 53.8 t ha\(^{-1}\); this value was 34.8% higher than in soil without compost. Considering that the trees were cut after three years of growing, the annual yield was 17.9 t ha\(^{-1}\) year\(^{-1}\). This yield was greater than in other short rotation coppices.
(SRC) of *Populus* I-214 in Mediterranean countries (Aravanopoulos, 2010; Sixto et al., 2007), probably due to the good weather conditions in the planting area and the longer growing season than the areas traditionally planted with poplars. In the case of *Eucalyptus*, at both sites, the highest biomass production was also found with the BC treatment (18.3 t ha\(^{-1}\) year\(^{-1}\) in RA and 19.7 t ha\(^{-1}\) year\(^{-1}\) in VI). In the case of RA, similar production was found in the treatment without amendment (Table 6). These yields were somewhat higher than the range found for *E. globulus* in SRC in South West Spain (13.9 - 14.6 t ha\(^{-1}\) year\(^{-1}\)) (Pérez-Cruzado et al., 2011). The *Paulownia* biomass production was lower than the other two studied species, showing the maximum yield in AC treatment (1.70 t ha\(^{-1}\) year\(^{-1}\)). This value was 28.4% and 53.0% higher than in BC and the treatment without compost, respectively. The yield of *Paulownia* in this study was similar to that finding in other SRC in the South of Spain (0.9 and 7.4 t ha\(^{-1}\) year\(^{-1}\); Durán et al., 2013).

**TABLE 6**

3.4. Nutrients in leaves of the fast-growing trees

Usually, when a soil is poor in nutrients, as in RA and VI soils, plants reflect this shortage in their leaves. Moreover, the amount of nutrients in leaves that will form the litter is fundamental for improving soil fertility (Kuzyakov and Domanski, 2000). In general, no differences due to compost addition were observed for any of the species (Figure 4). In VI soils, significantly higher values were observed in *Eucalyptus* for K in 2012 and 2013, and for P in 2013 in *Eucalyptus* and *Paulownia* (Figure 4). These results are in accordance with availability of both nutrients in the soil (Figure 2). Regarding *Paulownia*, Madejón et al. (2014) found similar results in plants growing in soils amended with similar composts. Nitrogen and P tended to decrease in time; in the case
of Ca and Mg, the opposite trend was observed (Figure S2), while K was quite similar
during the study. Pugnaire et al. (2001) also reported this pattern of accumulation in
leaves. In general, *Eucalyptus* leaves showed the lowest levels of nutrients, which is
related to the low nutrient concentrations and high concentration of secondary
compounds of this species (Canhoto and Graça, 1999).

FIGURE 4

Nutritional reference values, according to Mill and Jones (1991), are shown in Figure
4. In general, nutritional levels of the leaves were adequate except in a few cases.
Concentrations of N in *Eucalyptus* in 2013 and 2014 were below the adequate level for
this species at both sites, and P was below adequate levels in VI soils. In the case of
Paulownia, concentrations of P and K were below the adequate level established in the
literature. Potassium and P were abundant in both amendments, although this fact was
not reflected in the composition of the plant’s leaves. This could be related to the acidity
in VI soil, which decreased macronutrients availability for plants.

Micronutrients (Cu, Mn and Zn) in leaves (Figure 4 and S2) have also been studied
due to their presence in compost (Table 2) when their potential toxicity accumulation
reaches a certain level. However, there were no observed significant differences due to
the compost addition (Figure 4).

The highest concentrations of Cu were found in *Eucalyptus* growing in RA soils with
values above the adequate levels for this plant and with a maximum (100 mg kg\(^{-1}\)) at the
final sampling in BC treatment (Figure 4d). These data are due to the high levels of Cu
in soils (Table 5), and these concentrations in soil are typical of contaminated areas. The
levels in *Eucalyptus* leaves were quite high, more appropriate for a plant able to
accumulate this element, although there is no recorded information about this fact.
Poplar Cu concentrations were around 20 mg kg\(^{-1}\) (Figure 4d), which is in the same
range or even higher than values found in trees growing in a contaminated area (Ciadamidaro et al., 2014b). In *Paulownia* leaves, Cu concentrations were also found to be higher than necessary for this tree (Figure 4i). The ability of this species to accumulate Cu in soil (even at low levels) has been reported by other authors (Jiang et al., 2012; Madejón et al., 2014).

Concentrations of Mn were also higher in *Eucalyptus* compared to other trees. In RA soils, values were increasing in time (Figure S2), with concentrations at lower than adequate levels; although, in VI soil, leaves reached values around 4,000 mg kg\(^{-1}\) due to the acidic pH, the higher total content of this element in this soil (Table 5) and the ability of this species to accumulate this element (Hill et al., 2001).

Maximum concentrations of Zn were found in Poplar (Figure 4e), followed by *Paulownia* (Figure 4j). The ability of poplar to accumulate Zn has been widely reported (Madejón et al., 2013); however, concentrations in leaves were at the same level as poplar growing in contaminated soils (Ciadamidaro et al., 2014b).

### 4. Conclusions

This study has demonstrated that the addition of organic amendments, improved soil chemical and biochemical properties in low-fertility soils under plantations of poplar, eucalyptus and paulownia. The effects of compost were dependent on the initial characteristics of the soil, especially pH and TOC values. Moreover, these composts improved the biomass yield of these fast-growing trees, especially in the case of *Eucalyptus*, and when soil has acid pH. In this last regard, biosolid compost, an economic waste and used worldwide, showed better results. Results pointed out that the addition of both composts could be integrated solution to relieve the problem of the treatment and reuse of organic wastes increasing the quality and productivity of
degraded soils. At the same time, these soils could be used for plant biomass production dedicated to energy purposes compatible with sustainability policies. The soils that received the composts showed higher ability to accumulate CO$_2$ and to maintain soil pH close to neutrality, to increase fertility and quality and, therefore, they avoided soil impoverishment. This result will be reflected in a good cycling of nutrients in soils, which allows for sustainable management of degraded areas.

Acknowledgments

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Table 1. Soil general characteristics (Mean values; n=10, in brackets standard deviation)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RA</th>
<th>VI</th>
</tr>
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<tr>
<td>pH</td>
<td>6.49 (0.04)</td>
<td>4.68 (0.08)</td>
</tr>
<tr>
<td>EC (dS m(^{-1}))</td>
<td>91.4 (9.52)</td>
<td>68.9 (10.7)</td>
</tr>
<tr>
<td>TOC (g kg(^{-1}))</td>
<td>8.54 (3.63)</td>
<td>7.64 (3.99)</td>
</tr>
<tr>
<td>N-Kjel (g kg(^{-1}))</td>
<td>0.66 (0.17)</td>
<td>0.54 (0.27)</td>
</tr>
<tr>
<td>Avail-P (mg kg(^{-1}))</td>
<td>8.47 (1.57)</td>
<td>4.96 (0.16)</td>
</tr>
<tr>
<td>Avail-K (mg kg(^{-1}))</td>
<td>55 (7.55)</td>
<td>54.7 (4.72)</td>
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Table 2. Main characteristic of the amendments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Alperujo Compost</th>
<th>Biosolids Compost</th>
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<td>pH</td>
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<tr>
<td>Organic matter (%)</td>
<td>30.1</td>
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</tr>
<tr>
<td>N (%)</td>
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<td>2.27</td>
</tr>
<tr>
<td>P (%P₂O₅)</td>
<td>2.54</td>
<td>3.43</td>
</tr>
<tr>
<td>K (% K₂O)</td>
<td>2.30</td>
<td>0.82</td>
</tr>
<tr>
<td>Ca (% CaO)</td>
<td>13.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Mg (% MgO)</td>
<td>1.48</td>
<td>1.23</td>
</tr>
<tr>
<td>S (% SO₃)</td>
<td>0.90</td>
<td>2.24</td>
</tr>
<tr>
<td>As (mg kg⁻¹)</td>
<td>2.45</td>
<td>13.5</td>
</tr>
<tr>
<td>Cd (mg kg⁻¹)</td>
<td>0.25</td>
<td>1.94</td>
</tr>
<tr>
<td>Cu (mg kg⁻¹)</td>
<td>94.2</td>
<td>188</td>
</tr>
<tr>
<td>Mn (mg kg⁻¹)</td>
<td>360</td>
<td>573</td>
</tr>
<tr>
<td>Pb (mg kg⁻¹)</td>
<td>9.77</td>
<td>61.4</td>
</tr>
<tr>
<td>Zn (mg kg⁻¹)</td>
<td>185</td>
<td>601</td>
</tr>
</tbody>
</table>
Table 3. Allometric equations for total aboveground biomass estimations (M in g), biomass of leaves and of branches. a, b and c are the model's fitted parameters; N the sample size; Adj R²: coefficient of determination; D: stem diameter at the base (in mm); H: tree height (in cm). Available equations for trees with D > 10 mm and H > 90 cm

<table>
<thead>
<tr>
<th>Specie</th>
<th>Dry weight</th>
<th>Equation type</th>
<th>N</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Adj. R²</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E. globulus</em></td>
<td>Leaves</td>
<td>$M = a + bD + cH$</td>
<td>28</td>
<td>-825.400</td>
<td>27.560</td>
<td>1.145</td>
<td>0.930</td>
</tr>
<tr>
<td></td>
<td>Branches</td>
<td>$M = a + bD^2 + cH$</td>
<td>28</td>
<td>-1506.164</td>
<td>0.707</td>
<td>5.235</td>
<td>0.975</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$M = a + bD^2 + cH$</td>
<td>28</td>
<td>-1528.932</td>
<td>0.852</td>
<td>6.876</td>
<td>0.974</td>
</tr>
<tr>
<td><em>Populus I214</em></td>
<td>Leaves</td>
<td>$M = aD^b$</td>
<td>39</td>
<td>0.848</td>
<td>1.669</td>
<td></td>
<td>0.989</td>
</tr>
<tr>
<td></td>
<td>Branches</td>
<td>$M = aD^b$</td>
<td>39</td>
<td>0.021</td>
<td>2.870</td>
<td></td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$M = aD^b$</td>
<td>39</td>
<td>0.168</td>
<td>4.559</td>
<td></td>
<td>0.982</td>
</tr>
<tr>
<td><em>Pauwlonia</em></td>
<td>Leaves</td>
<td>$M = a + bD^2 + cH$</td>
<td>12</td>
<td>38.748</td>
<td>0.370</td>
<td>-3.323</td>
<td>0.996</td>
</tr>
<tr>
<td></td>
<td>Branches</td>
<td>$M = a + bD^2$</td>
<td>12</td>
<td>-748.251</td>
<td>0.729</td>
<td></td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$M = a + bD^2 + cH$</td>
<td>12</td>
<td>-641.408</td>
<td>1.157</td>
<td>-4.261</td>
<td>0.997</td>
</tr>
</tbody>
</table>
Table 4. Geometric mean of enzyme activities (GM) for different soils, species and treatments (mean values ± standard error, n=4). Rows with different letters show significant different per treatment and sampling.

<table>
<thead>
<tr>
<th>Site</th>
<th>Sampling</th>
<th>species</th>
<th>Non-amended</th>
<th>AC</th>
<th>BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rábida</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>PO</td>
<td>0.42±0.03</td>
<td>0.62±0.12</td>
<td>0.59±0.08</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>E</td>
<td>0.48±0.03</td>
<td>0.50±0.05</td>
<td>0.50±0.05</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>E</td>
<td>0.25±0.06 a</td>
<td>0.47±0.04 b</td>
<td>0.49±0.03 b</td>
<td></td>
</tr>
<tr>
<td>Villablanca</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>PA</td>
<td>1.00±0.13</td>
<td>1.13±0.17</td>
<td>1.26±0.17</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>E</td>
<td>0.91±0.13</td>
<td>0.98±0.05</td>
<td>1.34±0.23</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>E</td>
<td>0.84±0.03</td>
<td>1.06±0.10</td>
<td>1.12±0.19</td>
<td></td>
</tr>
</tbody>
</table>

AC: Alperujo compost; BC: biosolid compost
PO: Populus x canadensis; E: Eucalyptus globulus; PA: Paulownia fortunei
1, 2, 3: first, second and third sapling corresponding to the first, second and third year of study
Table 5. Trace elements concentrations in soils per treatment (mg kg\(^{-1}\))

<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Treatment</th>
<th>Cu</th>
<th>Mn</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rábida</td>
<td>PO</td>
<td>Non-amended</td>
<td>153</td>
<td>49.3</td>
<td>44.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC</td>
<td>165</td>
<td>62.7</td>
<td>48.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CB</td>
<td>166</td>
<td>67.7</td>
<td>61.9</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Non-amended</td>
<td>165</td>
<td>44.3</td>
<td>45.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC</td>
<td>166</td>
<td>69.2</td>
<td>54.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC</td>
<td>178</td>
<td>58.0</td>
<td>55.8</td>
</tr>
<tr>
<td>Villablanca</td>
<td>PA</td>
<td>Non-amended</td>
<td>6.23</td>
<td>196</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC</td>
<td>4.96</td>
<td>270</td>
<td>55.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC</td>
<td>4.30</td>
<td>268</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Non-amended</td>
<td>4.47</td>
<td>230</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC</td>
<td>5.23</td>
<td>181</td>
<td>21.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC</td>
<td>5.70</td>
<td>175</td>
<td>45.1</td>
</tr>
</tbody>
</table>

AC: Alperujo compost; BC: biosolid compost
PO: Populus x canadensis; E: Eucalyptus globulus; PA: Paulownia fortunei
Table 6. Estimated Biomass in t ha\(^{-1}\) of each plant species at the end of the experiment. Mean values ± standard error). For each species and site data with different letters differ significantly.

<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Treatment</th>
<th>LDW (t ha(^{-1}))</th>
<th>WDW (t ha(^{-1}))</th>
<th>TDW (t ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rábida</td>
<td><em>Populus</em></td>
<td>Non-amended (N=136)</td>
<td>6.03 ± 0.92</td>
<td>35.1 ± 8.42</td>
<td>39.9 ± 8.45a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC (N=92)</td>
<td>5.87 ± 0.48</td>
<td>32.2 ± 4.32</td>
<td>36.9 ± 4.32a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC (N=56)</td>
<td>7.66 ± 1.51</td>
<td>48.8 ± 13.6</td>
<td>53.8 ±13.9b</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus</em></td>
<td>Non-amended (N=377)</td>
<td>16.9 ± 3.00</td>
<td>37.6 ± 8.06</td>
<td>55.0 ± 11.1b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC (N=375)</td>
<td>14.0 ± 1.81</td>
<td>29.9 ±5.00</td>
<td>44.2 ± 6.81a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC (N=371)</td>
<td>17.2 ± 1.91</td>
<td>36.9 ± 4.55</td>
<td>54.8 ± 8.52b</td>
</tr>
<tr>
<td>Villablanca</td>
<td><em>Paulownia</em></td>
<td>Non-amended (N=120)</td>
<td>0.81 ± 0.20</td>
<td>3.00 ±1.00</td>
<td>3.34 ± 1.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC (N=120)</td>
<td>1.14 ± 0.27</td>
<td>4.55 ± 1.41</td>
<td>5.11 ± 1.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC (N=120)</td>
<td>0.96 ± 0.19</td>
<td>3.63 ± 0.98</td>
<td>3.98 ± 1.10</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus</em></td>
<td>Non-amended (N=120)</td>
<td>14.4 ± 1.38</td>
<td>27.6 ± 3.46</td>
<td>40.4 ± 4.86a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AC (N=120)</td>
<td>15.4 ± 1.84</td>
<td>35.2 ± 4.71</td>
<td>51.0 ± 6.56ab</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC (N=120)</td>
<td>17.7 ± 1.77</td>
<td>41.0 ± 4.66</td>
<td>59.2 ± 6.44b</td>
</tr>
</tbody>
</table>

LDW = Leaves dry weight; WDW = Woody dry weight  TDW = Total biomass dry weight
Figure 1. pH, Total organic carbon (TOC) and Water soluble Carbon (WSC) measured during the three-year experiment in La Rábida (RA) soils (a, b and c graphs) and Villablanca (VI) soils (d, e and f graphs). Significant differences (p<0.05) due to amendments for each species and sampling are marked with different letters.

PO: Populus without amendments; PO-AC Populus + Alperujo Compost; PO-BC Populus + Biosolid compost
E: Eucalyptus without amendments; E-AC Populus + Alperujo Compost; E-BC Populus + Biosolid compost
PA: Paulownia. without amendments; PA-AC Populus + Alperujo Compost; PA-BC Populus + Biosolid compost
Figure 2. N-kjel, available-P and available-K measured during the three-year experiment in La Rábida (RA) soils (a, b and c graphs) and Villablanca (VI) one (d, e and f graphs). Significant differences (p<0.05) due to amendments for each species and sampling are marked with different letters.
Figure 3. Cumulative growth of total aboveground biomass for each species over the three-year study in Populus (a) and Eucalyptus (b) at La Rábida (RA) site; Paulownia (c) and Eucalyptus (d) at Villablanca (VI) site. Mean values ± standard error.
Figure 4. Nutrients in Populus and Eucalyptus leaves at La Rábida (RA) site (a, b, c, d, e) and in Paulownia and Eucalyptus leaves at Villablanca (VI) one (f, g, h, i, j) (N, K and P in g 100g⁻¹, and Cu and Zn in mg kg⁻¹). Significant differences (p<0.05) due to amendments for each species and sampling are marked with different letters. Adequate levels for each species are showed for each element (Mills and Jones, 1991).