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

Paula Madejón ^{*1}, Joaquin Alaejos ², José García-Álbala ², Manuel Fernández ², Engracia Madejón ¹

¹ Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS), CSIC, Avenida Reina Mercedes 10, P.O. Box 1052, 41080 Sevilla, Spain

² Departamento de Ciencias Agroforestales. Escuela Técnica Superior de Ingeniería. Universidad de Huelva. Campus Universitario de La Rábida. Palos de la Frontera. 21819. Huelva, Spain.

*corresponding author: email: pmadejon@irnase.csic.es
Telephone: +34954624711 FAX +34954624002

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 CO₂ (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 (Vanguelova 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 processes (López Bermúdez and Albaladejo, 1990).

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 1

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

wastewater sludge from a water treatment plant and green waste from parks and gardens. The main characteristics of the two composts 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 Bremner (1969). Urease activity was determined according to the method proposed by Kandeler and Geber (1988) and modified by Kandeler et al. (1999).

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

Pseudo-total trace element concentrations in soil samples ($< 60 \mu\text{m}$) were determined by digestion with aqua regia (1:3 v:v conc. $\text{HNO}_3\text{:HCl}$) 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:

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

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) (Hazelton 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 1 c, 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 2 a, 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 2 c, 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

(Figures 2b, e). 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

3.3 Plant growth and biomass

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

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.

FIGURE 3

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 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 CO₂ 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

This study was mainly financed by the Autonomous Community of Andalusia RNM-6398, which were co-financed with FEDER funds (European fund for regional development). It also counted with substantial support of the research project AGL2010-16575 (Ministry of Science and Innovation, National Programme I+D+i). We thank the company ENCE, for providing the *Eucalyptus* nursery plants and for lending us the ground to install the Villablanca plot.

References

- Alguacil, M.M., Díaz-Pereira, E., Caravaca, F., Fernández, D.A., Roldán, A., 2009. Increased diversity of arbuscular mycorrhizal fungi in a long-term field experiment via application of organic amendments to a semiarid degraded soil. *Appl. Environ. Microbiol.* 75, 4254-4263.
- Alloway, B. J., 2013. Heavy Metals in Soils. Trace Metals and Metalloids in soils and their Availability. 3rd Edition. Springer, Dordrecht
- Aravanopoulos, F.A., 2010. Breeding of fast growing forest tree species for biomass production in Greece. *Biomass Bioenerg.* 34, 1531-1537.

428 Bååth, E., 1989. Effects of heavy metals in soil on microbial processes and
 429 populations (a review). *Water Air Soil Pollut.* 47, 335–379

430 Bouvet, A., Nguyen-The, N, Melun, F., 2013. Nutrient concentration and allometric
 431 models for hybrid eucalyptus planted in France. *Ann. For. Sci.* 70, 251–260.

432 Brady, N.C., Weil, R.R., 2002. *The Nature and Properties of Soils* 13th ed. Prentice
 433 Hall, Upper Saddle River, New Jersey.

434 Canhoto, C., Graça, M.A.S., 1999. Leaf barriers to fungal colonization and shredders
 435 (*Tipula lateralis*) consumption of decomposing *Eucalyptus globulus*. *Microb. Ecol.* 37,
 436 163–172

437 Ciadamidaro, L., Madejón, E., Puschenreiter, M., Madejón, P., 2013. Growth of
 438 *Populus alba* and its influence on soil trace element availability. *Sci. Total Environ.*
 439 454-455, 337–347.

440 Ciadamidaro, L., Madejón, P., Madejón, E., 2014a. Soil chemical and biochemical
 441 properties under *Populus alba* growing: Three years study in trace element contaminated
 442 soils. *Appl. Soil Ecol.* 73, 26-33.

443 Ciadamidaro, L., Madejón, E., Robinson, B., Madejón, P., 2014b. Soil plant
 444 interactions of *Populus alba* in contrasting environments. *J. Environ. Manage.* 132, 329-
 445 337

446 Cuvardic, M., Tveitnes, S., Krogstad, T., Lombnæs P., 2004. Long-term effects of
 447 crop rotation and different fertilization systems on soil fertility and productivity. *Acta*
 448 *Agric. Scand., B Soil Plant Sci.* 54,193-201

449 Dewis, J., Freitas, F., 1970. Método físicos y químicos de suelos y aguas. *Food*
 450 *Agric. Organ. Boletín de Suelo* 10.

451 Durán, V.H., Jiménez, J.A., Perea, F., Rodríguez, C.R., Francia, J.R., 2013. Biomass
 452 Yield Potential of Paulownia Trees in a Semi-Arid Mediterranean Environment (S
 453 Spain). Int. J. Renew. Energ. Res. 3, N°4.

454 Evangelou, M.W.H., Conesa., H.M., Robinson, B.H., Schulin, R., 2012. Biomass
 455 Production on Trace Element–Contaminated Land: A Review. Environ. Eng. Sci. 29, 9,
 456 823-839.

457 FAO, 2001. Future production from forest plantations. Forest Plantations Thematic
 458 Papers, Working Paper FP/13, Forest Resources Development Service. Forest
 459 Resources Division.

460 García-Morote, F.A., López-Serrano, F.R., Martínez-García, E., Andrés-Abellán, M.,
 461 Dadi, T., Candel, D., Rubio, E., Lucas-Borja, M.E., 2014. Stem Biomass Production of
 462 *Paulownia elongata* × *P. fortunei* under Low Irrigation in a Semi-Arid Environment.
 463 Forests 5, 2505-2520.

464 Gianfreda, L., Ruggiero, P., 2006. Enzyme activities in soil, in: Nannipieri. P.,
 465 Smalla, K. (Eds.), Nucleic Acids and Proteins in Soil. Springer, Berlin, pp. 20–25.

466 Hazelton, P., Murphy, B., 2007. Interpreting Soil Test Results: What do all the
 467 Numbers Mean? CSIRO Publishing, Collinwood, Victoria

468 Hesse, P.R., 1971. A Textbook of Soil Chemical Analysis. John Murray, London.

469 Hill, J., Attiwill, P.M., Uren, N.C., O'Brien, N.D., 2001. Does manganese play a role
 470 in the distribution of the eucalypts?. Aust. J. Bot. 49, 1–8.

471 Jiang, Z.-F., Huang, S.-Z., Han, Y.-L., Zhao, J.-Z., Fu, J.-J., 2012. Physiological
 472 response of Cu and Cu mine tailing remediation of *Paulownia fortunei* (Seem) Hemsl.
 473 Ecotoxicology 21, 759-767

474 Kandeler, E., Gerber, H., 1988. Short-Term assay of soil urease activity using
 475 colorimetric determination ammonium. Biol. Fertil. Soil 6, 68-72.

476 Kandeler, E., Stemmer, M., Klimanek, E.M., 1999. Response of soil microbial
 477 biomass, urease, and xylanase within particle size fraction to long-term soil
 478 management. *Soil Biol. Biochem.* 31, 261-273.

479 Kohler, J., Tortosa, G., Cegarra, J., Caravaca, F., Roldán, A., 2008. Impact of DOM
 480 from composted “alperujo” on soil structure, AM fungi, microbial activity and growth
 481 of *Medicago sativa*. *Waste Manag.* 28, 1423-1431.

482 Kuzyakov, Y., Domanski, G., 2000. Carbon input by plants into the soil. Review. *J.*
 483 *Plant Nutrit. Soil Sci.* 163, 421-431.

484 Lakhdar, A., Scelza, R., Ben Achiba, W., Scotti R., Rao M.A., Jedidi, N., Abdelly,
 485 C., Gianfreda, L., 2011. Effect of municipal solid waste compost and sewage sludge on
 486 enzymatic activities and wheat yield in a clayey-loamy soil. *Soil Sci.* 176, 15-21

487 Lauri, P., Havlík, P., Kindermann G., Forsell N., Böttcher, H., Obersteiner M., 2014.
 488 Woody biomass energy potential in 2050. *Energy Policy* 66, 19–31.

489 López Bermúdez, F., Albaladejo, J., 1990. Factores ambientales de la degradación
 490 del suelo en el área mediterránea, in: Albaladejo, J., Stocking, M.A., Díaz, E. (Eds.),
 491 *Soil Degradation and Rehabilitation in Mediterranean Environmental Conditions*,
 492 CEBAS-CSIC, Madrid.

493 Madejón, P., Ciadamidaro, L., Marañón, T., Murillo, J.M., 2013. Long-Term
 494 Biomonitoring of Soil Contamination Using Poplar Trees: Accumulation of Trace
 495 Elements in Leaves and Fruits. *Int. J. Phytoremediat.* 15, 602–614,

496 Madejón, P., Xiong, J., Cabrera, F., Madejón, E., 2014. Quality of trace element
 497 contaminated soils amended with compost under fast growing tree *Paulownia fortunei*
 498 plantation. *J. Environ. Manage.* 144, 176-185

Mengual, C., Schoebitz, M., Azcón, R., Roldán, A., 2014. Microbial inoculants and organic amendment improves plant establishment and soil rehabilitation under semiarid conditions. *J. Environ. Manage.* 134, 1-7

Mills, H., Jones, J.B., 1991. *Plant Analysis Hand Book II*. MicroMacro Publishing, Inc., United States

Molinero, J., Pozo, J., 2004. Impact of a eucalyptus (*Eucalyptus globulus* Labill.) plantation on the nutrient content and dynamics of coarse particulate organic matter (CPOM) in a small stream. *Hydrobiologia* 528, 143–165.

Naramabuye, F.X., Haynes, R.J., 2006. Effect of organic amendments on soil pH and Al solubility and use of laboratory indices to predict their liming effect. *Soil Sci.* 171, 754–763.

Ngao, J., Bernhard-Reversat, F., Loumeto, J.J., 2009. Changes in eucalypt litter quality during the first three months of field decomposition in a Congolese plantation. *Appl. Soil Ecol.* 42, 191–199.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. U.S. Department of Agriculture. Report 939.

Pannacci, E., Bartolini, S., Covarelli, G., 2009. Evaluation of four poplar clones in a short rotation forestry in Central Italy. *Ital. J. Agron.* 4, 191-198.

Paris, P., Mareschi, L., Sabatti, M., Pisanelli, A., Ecosse, A., Nardin, F., Scarascia-Mugnozza, G., 2011. Comparing hybrid *Populus* clones for SRF across northern Italy after two biennial rotations: survival, growth and yield. *Biomass Bioenerg.* 35, 1524-1532.

522 Pascual, J.A., Hernández, T., García, C., García, A., 1998. Changes in the organic
 523 matter mineralization rates of an arid soil after amendment with organic wastes. *Arid*
 524 *Soil Res. Rehab.* 12, 63–72.

525 Paz-Ferreiro, J., Gascó, G., Gutiérrez, B., Méndez, A., 2012. Soil biochemical
 526 activities and the geometric mean of enzyme activities after application of sewage
 527 sludge and sewage sludge biochar to soil. *Biol. Fertil. Soils* 48, 511–517

528 Pérez-Cruzado, C., Merino, A., Rodríguez-Soalleiro, R., 2011. A management tool
 529 for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus*
 530 and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain.
 531 *Biomass Bioenerg.* 35, 2839-2851

532 Pugnaire, F.I., 2001. Variability of inorganic nutrients in leaves. *New Phytologist*
 533 150, 506-507

534 Qualls, R.G., Haines, B.L., Swank, W.T., 1991. Fluxes of dissolved organic nutrients
 535 and humic substances in a deciduous forest. *Ecology* 72, 254–266.

536 Quaye, A.K., Volk, T.A., Hafner, S., Leopold, D.J., Schirmer, C., 2011. Impacts of
 537 paper sludge and manure on soil and biomass production of willow. *Biomass Bioenerg.*
 538 35, 2796-2806

539 Rashid, A., Ryan J., 2004. Micronutrient constraints to crop production in soils with
 540 Mediterranean-type characteristics: A review. *J. Plant Nutr.* 27, 959-975.

541 Rhoades, C., Binkley, D., 1996. Factors influencing decline in soil pH in Hawaiian
 542 *Eucalyptus* and *Albizia* plantations. *For. Ecol. Manage.* 80, 47-56

543 Ros, M., Hernández, M. T., García, C., 2003. Soil microbial activity after restoration
 544 of a semiarid soil by organic amendments. *Soil Biol. Biochem.* 35, 463–469.

545 Sixto, H., Hernández, M. J., Barrio, M., Carrasco, J., Cañellas, I., 2007. Plantaciones
 546 del género *Populus* para la producción de biomasa con fines energéticos: revisión (in
 547 Spanish). *Investig. Agrar., Sist. Recur. For.* 16, 277-294
 548 Stevenson, F. J., 1982. *Humus Chemistry: Genesis, Composition, Reactions*. Wiley
 549 Interscience Publications. John Wiley and Sons, New York.
 550 Tabatabai, M.A., 1982. Soil enzymes, in: Page, A.L., Miller, E.M., Keeney, D.R.
 551 (Eds.), *Methods of Soil Analyses. Part 2. Chemical and Microbiological Properties*.
 552 American Society of Agronomy, Madison, pp. 903-947.
 553 Tabatabai, M.A., Bremner, J.M., 1969. Use of p-nitrophenyl phosphate for assay of
 554 soil phosphatase activity. *Soil Biol. Biochem.* 1, 301-307.
 555 Trevors, J.T., 1984. Dehydrogenase activity in soil: a comparison between the INT
 556 and the TTC assay. *Soil Biol. Biochem.* 16, 673–674.
 557 Vanguelova, E., Pitman, R., 2009. Impacts of short rotation forestry on soil
 558 sustainability, in: McKay, H. (Ed.), *Short Rotation Forestry: Review of Growth and*
 559 *Environmental Impacts : Forest Research Monograph, 2. Forest Research*, pp. 37–78.
 560 Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for
 561 determining soil organic matter and a proposed determination of the chromic acid
 562 titration method. *Soil Sci.* 37, 29-38.

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

Parameter	RA	VI
pH	6.49 (0.04)	4.68 (0.08)
EC (dS m ⁻¹)	91.4 (9.52)	68.9 (10.7)
TOC (g kg ⁻¹)	8.54 (3.63)	7.64 (3.99)
N-Kjel (g kg ⁻¹)	0.66 (0.17)	0.54 (0.27)
Avail-P (mg kg ⁻¹)	8.47 (1.57)	4.96 (0.16)
Avail-K (mg kg ⁻¹)	55 (7.55)	54.7 (4.72)

Table 2. Main characteristic of the amendments.

Parameter	Alperujo Compost	Biosolids Compost
pH	8.10	7.09
Organic matter (%)	30.1	24.6
N (%)	1.56	2.27
P (% P ₂ O ₅)	2.54	3.43
K (% K ₂ O)	2.30	0.82
Ca (% CaO)	13.8	12.5
Mg (% MgO)	1.48	1.23
S (% SO ₃)	0.90	2.24
As (mg kg ⁻¹)	2.45	13.5
Cd (mg kg ⁻¹)	0.25	1.94
Cu (mg kg ⁻¹)	94.2	188
Mn (mg kg ⁻¹)	360	573
Pb (mg kg ⁻¹)	9.77	61.4
Zn (mg kg ⁻¹)	185	601

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

Specie	Dry weight	Equation type	N	<i>a</i>	<i>b</i>	<i>c</i>	Adj. R ²
<i>E. globulus</i>	Leaves	$M = a + bD + cH$	28	-825.400	27.560	1.145	0.930
	Branches	$M = a + bD^2 + cH$	28	-1506.164	0.707	5.235	0.975
	Total	$M = a + bD^2 + cH$	28	-1528.932	0.852	6.876	0.974
<i>Populus I214</i>	Leaves	$M = a D^b$	39	0.848	1.669		0.989
	Branches	$M = a D^b$	39	0.021	2.870		0.971
	Total	$M = a D^b$	39	0.168	4.559		0.982
<i>Pauwlonia</i>	Leaves	$M = a + bD^2 + cH$	12	38.748	0.370	-3.323	0.996
	Branches	$M = a + bD^2$	12	-748.251	0.729		0.995
	Total	$M = a + bD^2 + cH$	12	-641.408	1.157	-4.261	0.997

Table 4. Geometric mean of enzyme activities (GM) for different soils, species and treatments (mean values $\pm$ standard error, n=4). Rows with different letters show significant different per treatment and sampling

Site	Sampling	species	Non-amended	AC	BC
Rábida	1	PO	0.42 $\pm$ 0.03	0.62 $\pm$ 0.12	0.59 $\pm$ 0.08
	2		0.22 $\pm$ 0.06	0.31 $\pm$ 0.05	0.30 $\pm$ 0.07
	3		0.34 $\pm$ 0.11	0.41 $\pm$ 0.08	0.66 $\pm$ 0.13
	1	E	0.48 $\pm$ 0.03	0.50 $\pm$ 0.05	0.50 $\pm$ 0.05
	2		0.15 $\pm$ 0.03	0.25 $\pm$ 0.08	0.34 $\pm$ 0.04
	3		0.25 $\pm$ 0.06 a	0.47 $\pm$ 0.04 b	0.49 $\pm$ 0.03 b
Villablanca	1	PA	1.00 $\pm$ 0.13	1.13 $\pm$ 0.17	1.26 $\pm$ 0.17
	2		0.90 $\pm$ 0.09	1.01 $\pm$ 0.06	1.16 $\pm$ 0.11
	3		0.36 $\pm$ 0.07	0.41 $\pm$ 0.06	0.46 $\pm$ 0.08
	1	E	0.91 $\pm$ 0.13	0.98 $\pm$ 0.05	1.34 $\pm$ 0.23
	2		0.84 $\pm$ 0.03	1.06 $\pm$ 0.10	1.12 $\pm$ 0.19
	3		0.32 $\pm$ 0.04 a	0.51 $\pm$ 0.06 b	0.46 $\pm$ 0.04 ab

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)

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

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 $\pm$ standard error). For each species and site data with different letters differ significantly.

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

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.

Figure3. 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 $\pm$ standard error.

Figure 4 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).