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Use of composted urban waste in the reforestation of a degraded calcic regosol in Central Spain

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INTRODUCTION. – Soil organic matter (OM) plays an active role in regulating the composition of the soil solution, and has a direct bearing on both the bioavailability of mineral ions and soil water-holding capacity. Indeed, a steady reduction in the soil OM content is one of the main factors associated with the irreversible loss of valuable soil physical and chemical properties (ALBADALEJO *et al.*, 1994; LÓPEZ-BERMÚDEZ *et al.*, 1990) and soil degradation (GARCÍA *et al.*, 1992) in semiarid environments.

Organic amendments have traditionally been used to improve the hydraulic properties (ROMÁN *et al.*, 2003) of soil and to promote its aggregation; the highly positive effects of OM on soil structure as well as on its physical, chemical and biological properties (HAYES, 1986; MBAGWU, 1992; OADES, 1984) are well known. However, amending agents from a variety of natural sources (e.g., cattle manure) are becoming increasingly scarce. Interest in the possible use of composted urban waste (CUW) has therefore been growing.

The extent to which high doses of compost influence plant survival and soil physico-chemical properties has not been extensively studied (KIELHORN *et al.*, 1999; ROMÁN *et al.*, 2003). In a previous paper we demonstrated the efficiency of adding 400 Mg ha^{-1} of compost to soil with poor physical and chemical properties under semiarid conditions (ROMÁN *et al.*, 2003). This treatment had beneficial effects on soil bulk density, saturated hydraulic conductivity and water availability, and hence alleviated the soil's erosion problems. Moreover, the massive application of compost promoted the formation of stable aggregates through interactions among the OM, clay, and compost-derived transition ions. These interactions also improved hydraulic conductivity. As a result, the soil was able to support several plant species.

As part of a reforestation project, the aim of the present study was to assess, in pots, the effects of high doses of CUW (40 and 100 g

kg^{-1} soil) on a degraded calcic-gypsic soil with extremely unfavourable physical properties and negligible OM content, and on the Aleppo pine (*Pinus halepensis*) trees growing in this soil. This species is adapted to semiarid Mediterranean conditions and is commonly used in reforestation projects. Throughout the experiment, the water potential was monitored to ensure that each plant was subjected to the same water stress conditions.

METHODS AND MATERIALS. – *Urban waste.* – The matured compost used in this work was produced at an urban waste processing station in Valdemingomez (Madrid, Spain). The compost was the organic fraction left behind after removing the ferromagnetic, glass, plastic, paper and inert residues etc. by successive passage of the compost through separation devices (magnets, fans, hot rotary cylinders and a flotation tank). The resultant OM-rich material was then mechanically rotated for a standard three-month composting period. The contaminant metal levels in the CUW were not toxic according Spanish law.

Soil. – The soil at the reforestation site was a Leptosol-Calcic Regosol (FAO, 1989) developed on colluvial materials (mainly gypsic marls and limestones). Particle sizes >2 mm accounted for 72% of the soil dry weight and included a large proportion (820 g kg^{-1}) of gypsum and calcite crystals. The fine fraction (<2 mm) consisted of 610 g kg^{-1} sand, 170 g kg^{-1} clay and 220 g kg^{-1} silt. The soil texture class was «loamy sand» (GTNMA, 1973). Stable aggregates amounted to 232 g kg^{-1} and the silt+clay fraction 390 g kg^{-1}; the mean instability index (l_s) was 2.62 (HENIN and MONNIER, 1972). The available nutrients included Mg (150 mg Kg^{-1}), Mn (59 mg Kg^{-1}), Fe (44 mg Kg^{-1}), Al (10 mg Kg^{-1}) and Cu (1 mg Kg^{-1}).

Experimental design. – Experimental work was performed in 12 pots (0.6x0.6x1.0 m) in a field at the La Poveda field station (Arganda del Rey, 25 km east of Madrid); the intention behind this use of pots was to overcome the effects of the mosaic of different soil chemical and physical properties recorded at the reforestation site, which could have led to erratic results. The pots were made of concrete and were lined with an impermeable layer of pigmented polypropylene. They were positioned 0.3 m above the ground. The base of each pot had a 30 mm diameter hole fitted with a funnel to collect leachate.

A 10 mm layer of gravel was added to the base of each pot. Four pots were then filled with CUW-free soil, four with soil amended with 40 g CUW per kg soil (dry weight) (equivalent to 120 Mg ha^{-1}), and four with soil treated with 100 g CUW per kg soil (dry weight) (equivalent to 300 Mg ha^{-1}). Such large CUW doses have been described suitable for reforestation purposes due to their increasing the soil's water holding capacity, capillarity, porosity and conductivity. This in turn favours root development (ROMÁN *et al.*, 2003). To determine the soil bulk density, soil samples were taken from each pot at depths of 0.15 m, 0.3 m, and 0.5 m using a cylinder 40 mm high and 70 mm in diameter.

Seedlings were planted in December, marking the start of a two year experimental period. The four pots per treatment and nine plants per pot rendered a total of 36 plants per treatment. During the summer, the pots were protected by a 1 m-high net, which reduced the impact of the direct sunlight on the walls of the pots.

To guarantee that any differences in growth were due exclusively to the compost, water stress was eliminated. For this, a tensiometer was placed at a depth of 0.3 m in each pot. Data were collected on a monthly basis from November to February, and at intervals as short as every three days during periods of heavy water consumption. The pots were watered when the water potential was at least –65 kPa to ensure similar levels of maximum water stress in all treatments.

A soil sample was taken at a depth of around 0.10 to 0.15 m in each plot at 9, 18, and 24 months after planting. These samples were air-dried, sieved (mesh size 2 mm), and used to determine the proportion of soil aggregates and their stability (HENIN *et al.*, 1972), the total nutrient content (GTNM, 1973), and the concentrations of available nutrients (LAKANEN & ERVIO, 1971) (NH_4Ac - EDTA mixture). The different nutrient contents were determined by atomic absorption spectroscopy and plasmainduced spectroscopy.

Water consumption in each pot was calculated using the following water balance equation:

Evapotranspiration + Drainage = Rainfall + Irrigation + Variation in the soil water reserve.

Rainfall, irrigation and drainage data were obtained experimentally. The variation in the soil water reserve was minimized by taking into account long periods (one month or longer) and making use of days following similar events (such as considerable rainfall or irrigation) as reference dates when calculating the evapotranspiration rate. Any change in the soil water reserve would therefore be small compared with the other variables.

The height and basal diameter of the Aleppo pines were periodically recorded during the study period. Two trees per pot were cut down at nine months. At the end of the experiment, a further two per pot were cut down in order to determine their biomass (thus leaving five pines in each pot). Shoot biomass data were used to derive formulae relating this variable to the height and basal diameter of the trees; the biomass could therefore be estimated for the entire set of trees. Statistical tests were performed using SPSS v11.5 software.

RESULTS AND DISCUSSION. – *Effects on bulk density.* – The mean soil bulk density of the 12 determinations per treatment were: 1.05±0.11 Mg m^{-3} for the untreated soil, 1.01±0.08 Mg m^{-3} for the soil amended with 40 g kg^{-1} CUW, and 0.96±0.09 Mg m^{-3} for the soil receiving the 100 g kg^{-1} dose; differences among treatments were significant ($P \leq 0.01$). These results confirm our previous finding that soil density is reduced by approximately 0.01 Mg m^{-3} for every percentage unit of CUW added (GARCÍA *et al.*, 2002).

Effects on soil aggregate stability. – Increases in structural stability are indicated by decreases in the instability index $(l_s)//(l_s = \%$ aggregates/(% silt+clay)–(0.9% sand) (HENIN *et al.*, 1972). In the untreated soil, no significant difference was seen with respect to the native soil at 8 months, although significant ($p \leq 0.01$) improvements were observed at 18 and 24 months (Table 1). With the applications of 40 and 100 g CUW kg^{-1} soil however, the structural stability of the soil had improved at 8 months ($p \leq 0.01$). At 18 and 24 months a significant ($p \leq 0.01$) improvement was observed with respect to the native soil. No significant differences were seen between 18 and 24 months in any treatment.

The improvement in structural stability was also reflected by the significant increase ($p \leq 0.01$) observed in the percentage of aggregates. The new aggregates were formed from the silti-clay fraction, which diminished significantly as the percentage of aggregates increased. The percentages of aggregates at 18 and 24 months in the 40 and 100 g CUW kg^{-1} soil treatments were higher than in untreated soil at these times. At eight months the increase in aggregates could be a result of a binding effect caused by the roots leading to the formation of new soil structures.

By the end of the two-year study period, the proportion of aggregates in the soil (230 g stable aggregates kg^{-1}) had greatly increased in all treatments. Two thirds of this increase was due to the effects of root growth (i.e., compared to the native soil without vegetation), while one third was due to the organic matter applied (Table 1).

Effects on soil chemical composition. – The concentrations of some EDTA-extractable nutrients decreased over time (Table 1); these reductions may be explained by tree uptake, leaching, or the formation of clay-polyvalent metal-OM complexes (the basic structural units – domains – giving give rise to new aggregates) (RIGHI and LOPHELIN, 1987). The elements not lost through root uptake or leaching form part of the aggregate fraction and become unavailable to the trees. Accordingly, available Mg and Mn were reduced in all treatments, available Cu, Al and Fe were reduced by both CUW doses (the levels of Ca, Na, K, Mg, Fe, Mn Zn, Al, Cu, Cd and Pb were all studied, but only the EDTA-extractable levels of Mg, Mn, Fe, Al and Cu were reduced). The chemical nature of Cu, Al, and Fe, which have large ionic radii and atomic weights, coupled with their tendency to form strong complexes, may contribute to the residual effect of this organic material.

These findings are consistent with those of our previous studies (FORTÚN & FORTÚN, 1996; ROMÁN *et al.*, 2003). The aggregating effect of the compost is attributable to its hydrophobic fraction

TABLE 1. – *Changes over time in stable aggregates, the silt+clay fraction, instability index and available elements in CUW-treated soil treated.*

CUW g. kg^{-1}	Time (months)	% Ag*	% silt+clay	I_s**	Mg (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Al (mg kg^{-1})	Cu (mg kg^{-1})
0	8	28.2 a	42.1 e	1.9 c	172 d	53 c	43 a	12 ab	2 a
0	18	37.2 b	36.1 d	1.2 b	61 ab	33 a	36 a	12 ab	2 a
0	24	40.2 b	35.2 d	1.1 ab	43 a	38 b	40 a	7 a	1 a
40	8	35.9 b	33.6 d	1.3 b	197 e	59 d	115 d	19 c	21 c
40	18	43.7 c	27.6 b	0.8 a	55 ab	37 b	105 c	25 d	15 b
40	24	46.4 c	30.6 c	0.9 a	61 ab	36 ab	90 b	11 ab	14 b
100	8	37.2 b	27.3 b	1.0 ab	240 f	60 d	185 f	30 d	37 d
100	18	43.1 c	24.4 a	0.8 a	74 bc	39 b	138 e	27 d	21 c
100	24	49.2 c	27.5 b	0.8 a	88 c	34 ab	106 c	14 bc	21 c

* Stable aggregates; ** Instability Index
Values with the same letter are not significantly different at $p \leq 0.01$.

(METZGER & YARON, 1987) and to its low-molecular-weight soluble aliphatic fraction (fulvic acid) (FORTÚN *et al.*, 1990). These fractions prevent the release of Fe, Mn and Al, which become trapped within the aggregates. Hence, newly formed aggregates remained stable for long periods, conferring a lasting structure on the soil, thus promoting plant growth. In agreement with the model proposed by TISDALL & OADES (1982), persistent particles (≤0.2 mm) of humic material associated with amorphous Fe and Al compounds would have contributed to a longer lasting soil stability that favoured root penetration. An improvement in soil structure was also observed, however, in the untreated soil after 18 months. This might be explained by the formation of transient and easily degradable macroaggregates by roots and fungal hyphae. The inner structure of these aggregates, however, would be unstable since they would lack the aforementioned metal ions.

Evapotranspiration, irrigation and rainfall. – The climatic conditions were normal over the experimental period (i.e., similar to the long-term averages for the area). Irrigation was required between June and September; July and August were the months during which the treatments were most frequently watered in both years. In the first year the mean drainage (29.3 l pot^{-1}), irrigation (82 l pot^{-1}) and end evapotranspiration (306.7 l pot^{-1}) were the same in all treatments. From June to September of the second year, however, considerable differences in water potential were observed between the pines growing in the soil amended with 40 and 100 g kg^{-1} CUW and those growing in the unamended soil. Consequently, the amount of irrigation water needed in the two treatments was 25% greater than that required with the untreated soil (217 l compared to 174 l). Moreover, the improved growth of all the trees recorded in the second year resulted in the amount of irrigation water required having to be increased compared to the previous year. Evapotranspiration values of 362.2 l pot^{-1} were recorded for the treated pots compared to 306.7 l pot^{-1} for the untreated pots.

Since the number of trees in the pots varied over the trial, evapotranspiration was calculated per tree for each treatment over the two years; Figure 1 shows the mean values.

In the first year, the ratio between evapotranspiration in the summer and winter was 2. However, it ranged between 4 and 8 during the second year.

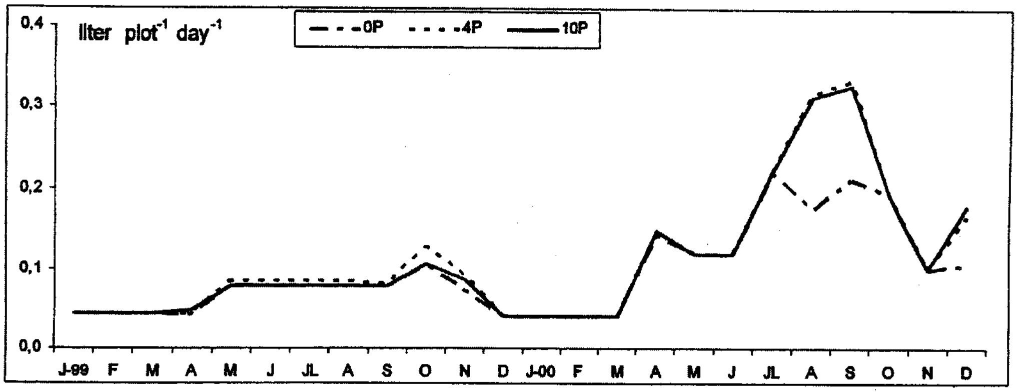

FIG. 1. – Evapotranspiration over the experiment (n = 36 from January to September [first year]; n = 28 from October [first year] to November [second year], and n = 20 for December (second year]).

Effects of soil remediation on the growth of the pines. –Monitoring the heights of the pine trees over 725 days (Fig. 2) revealed three stages of growth over the two years of the experiment. In the first stage there were no significant differences in tree heights

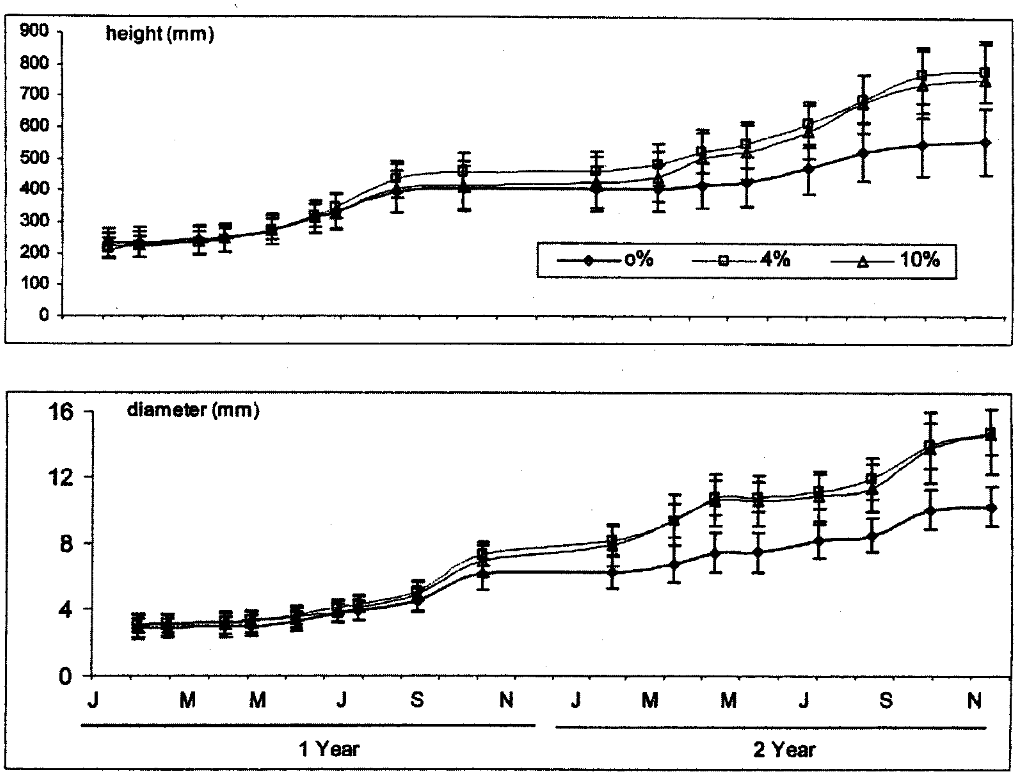

FIG. 2. – Aleppo pine height and diameter throughout the experiment in soil treated with CUW 0% (0 g CUW kg^{-1} soil), 4% (40 g CUW kg^{-1} soil) and 10% (100 g CUW kg^{-1} soil).

attributable to the application of CUW. In the second stage, some variation became apparent between those pines grown in the untreated soil and those grown in the soil amended with 40 g CUW kg^{-1} soil. In the third stage, however, marked differences were observed between trees growing in the nontreated and treated soil (irrespective of the dose added). Figure 2 shows the changes in the basal diameter of the pines according to treatment. These results indicate that from day 320, CUW had a beneficial effect on stem growth.

Two growth periods were observed each year: a rapid growth spurt when mean temperatures exceeded 10°C (March to October), and slow growth when temperatures dropped below 10°C (November to February). When temperature increased in February, no significant growth differences were noted among the treatments. When the pines began to grow in the first year their nutrient requirements were low and all the soils were able to provide sufficient nutrients, delaying the observation of any effects of soil treatment.

An equation was formulated that correlated pine biomass with height and basal diameter at two different times: at the end of the first summer (when there were visible differences in these variables), and at the end of two years. For the end of the first summer, the equation was

$W_{p1} = 0.755 \times D^2 + 0.228 \times H - 5.434$ $R^2 = 0.752$ $n = 24$ (Eq. 1)

and for the end of the two years,

$W_{p2} = 1.385 \times D2 + 0.401 \times H - 45.13$ $R^2 = 0.869$ $n = 24$ (Eq. 2)

where W_p indicates the weight of each pine (g), D the basal diameter (mm), and H the height (cm).

Significance for R^2 was set at $p \leq 0.01$.

Weight was estimated for the pines using Equation 1 for the first 18 months of the trial, and using Equation 2 for the rest of the trial.

Differences in aerial biomass among treatments started to gain significance from September, when pines growing in the soil treated with 40 g CUW kg^{-1} soil showed a 25% increase compared to those in the untreated soil ($p \leq 0.001$).

Pine growth continued in September and October (when the mean temperatures were 20.9°C and 15.6°C respectively). During this time, a greater increase in biomass was observed in the compost treatments – 40% for the 40 g CUW kg^{-1} soil and 25% for the 100 g CUW kg^{-1} soil treatments ($p \leq 0.01$ in both cases. Thus, the pines in the untreated soil increased in weight by 100 mg per day from March to October in the first year, while those in the 40 and 100 g CUW kg^{-1} soil treatments increased their weight by 140 and 130 mg per day.

This period was followed by a colder period (mean temperatures <10°C) which lasted from November to February. During this time, the pines in all treatments grew more slowly. Daily weight increases of 10, 90 and 100 mg were recorded for the 0, 40, and 100 g CUW kg^{-1} soil treatments respectively. Following this period, the newly rising temperatures were associated with growth differences among the treatments: a daily increase of 780 mg was recorded for the trees in the amended soils compared to 320 mg per day for those in the untreated soil.

The nutrient demands of the pines during the second year were higher than could be provided by the soil alone. As a result, the added compost had a positive effect on growth in both treatments. By the end of the experimental period the biomass observed in the CUW treatments was as much as 136% ($p \leq 0.01$) higher than that recorded for the unamended soil. This growth difference is consistent with the increased water consumption of the pines growing in the amended soil (independent of the compost dose).

Adding certain doses of compost to soils improves their physical and chemical properties, which in turn has a positive effect on the growth of crops. However, high doses of compost may fail to have an effect or even have a detrimental effect. The indiscriminate use of compost is therefore not recommended. The potential negative effects of the excessive use of organic compost include increased soil salinity and higher heavy metal and micro-pollutant concentrations. The highest dose in the present study, however, had no adverse effects on the trees.

The positive effects observed as a result of the present treatments are mainly attributable to the extra nutrients provided by the compost (Roldán *et al.*, 1996) and to the contributions made to soil aggregate stability. The increase in biomass observed over the two years were similar for both CUW doses provided, suggesting that sufficient nutrients were provided by the 40 g kg^{-1} treatment.

CONCLUSIONS. – The application of high doses of CUW improved the physical condition of a degraded soil (LeptosolCalcic Regosol) from a semiarid Mediterranean area. The bulk density was diminished and the proportion of stable aggregates increased. This favoured root penetration and development. Consequently, the water consumption of the trees growing in the amended soils became higher (since water stress was constant). After two years, the biomass of the pines growing in either treated soil was 2.4 times that recorded in the non-amended soil.

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SUMMARY. – Remediation options for a highly degraded soil were tested through the application of urban waste composted for three months (CUW). Soil physical and chemical properties were monitored for two years, and the growth of

planted Aleppo pine seedlings evaluated. The treatments applied were 0, 40 and 100 g CUW per kg soil (dry weight), equivalent to 0, 120 Mg ha^{-1} and 300 Mg ha^{-1}. Each dose was applied to four containers of 0.216 m^3 capacity with 9 plants in each. Soil water potential was monitored and evapotranspiration calculated using water balance equations. Soil amendment reduced the soil bulk density and improved the structure of the soil by increasing its stable aggregate content. After two years, the pine biomass produced in either treated soils was 2.4 times higher than in the untreated soil.