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ORIGINAL ARTICLE

Understanding compost effects on water availability in a degraded sandy soil of Patagonia

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Abstract Disturbances have the potential to reduce soil water and nutrient retention capacity by decreasing soil organic matter (SOM), which is particularly true for sandy soils characterized by an inherent low capacity to retain nutrients and water. To restore degraded areas, several works have shown positive effects of organic matter inputs on soil properties and plant growth. Despite these promising results, it is still unclear how organic matter inputs and plant growth modify the balance between soil nutrient and water supply. The objectives of the present work were (1) to evaluate the effects of biosolids compost and municipal compost addition on plant available water (PAW), soil moisture and soil temperature in a burned sandy soil of NW Patagonia (Argentina), and (2) to relate PAW and soil moisture with bulk density, soil organic carbon, nutrient availability (inorganic and potential mineralized nitrogen (N), extractable phosphorous) and aboveground phytomass. An experiment with excised vegetation and watering was also conducted. Compost application increased SOM, but it was insufficient to increase PAW. The increase in potential mineralized N in the amended soils indicated that during moist periods (and adequate temperatures), N uptake was increased, enhancing plant growth. As a consequence, higher plant water consumption in amended treatments resulted in lower soil moisture than in non-amended plots during the vegetative growth period that coincides with decreasing precipitation. Results indicate that a relatively high dose of compost (40 Mg ha^{-1}) applied to a sandy soil, contributed to increase nutrient availability and consequently, aboveground phytomass and water consumption.

Keywords Biosolids compost · Municipal compost · Restoration · Organic amendments · Field capacity · Permanent wilting point

Introduction

Drylands represent almost 41% of the worldwide land; currently, 10–20% of these lands are severely degraded and this trend is still expanding in many countries in the face of population growth, climate change, food security and rural poverty (Reynolds et al. 2007; Vieira et al. 2015; Cheng et al. 2016). Dryland soils are often coarse textured due to scant moisture and low weathering rates (Cooke et al. 1993); these soils have a very low capacity to retain nutrients and water, which affects vegetation growth and reduces the amounts of organic matter entering the soil. Disturbances can further reduce the soil capacity to retain water and nutrients by decreasing soil organic matter (SOM) (Suzuki et al. 2007; Uzoma et al. 2011). The use of organic amendments increases the amount of available nutrients and has long-term effects on nutrient and water dynamics (Clapp 2007; Reeve et al. 2012; Srivastava et al.

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2016). Several authors demonstrated the positive effects of organic matter inputs on soil physical properties, largely due to SOM increase and the improvement of soil aggregation and pore space distribution (Khaleel et al. 1981; Hudson 1994; Garcia-Orenes et al. 2005; Wortmann and Shapiro 2008; García Navarro et al. 2009). However, in sandy soils the effects of organic amendments tend to be short-term, even in semiarid regions where organic matter decomposition is constrained by unfavorable conditions for microbial activity (Feller et al. 1983; Weber et al. 2007; Aranyos et al. 2016). Long-lasting effects have been reported for sandy soils under xeric soil moisture regime, as in Mediterranean climate, where organic matter decomposition is strongly limited by the asynchrony between temperature and water availability (Martínez et al. 2003; Walter et al. 2006; Bastida et al. 2008). In these regions, the positive effects of organic amendments on aboveground phytomass have been attributed to increases in soil microbial activity and nutrient availability (Walter et al. 2006; Bastida et al. 2008; Kowaljow et al. 2010); however, results could be also influenced by higher water availability due to increased SOM. Then, the effects of organic amendments on plant biomass would depend on the balance between nutrient (especially nitrogen and phosphorus) and water supply.

The persistence of soil carbon (C) is related to the content of reactive mineral particles such as clay and silt that contribute to SOM stabilization, physical protection from decomposers and soil structure formation (Wortmann and Shapiro 2008; Ryals et al. 2014). In sandy soils, these processes are much less effective, and the persistence of added C is more related to the degradability of the organic matter itself (Weber et al. 2007; Arthur et al. 2011; Castán et al. 2016). This depends on the composition of the original materials used for composting, i.e., the amount and proportion of recalcitrant C (Gabrielle et al. 2004), and whether or not the final product is screened, as unscreened composts rich in slowly decomposable C are often recommended to enhance infiltration into compacted soil and reduce evaporation of soil water (Rynk et al. 1992; McCoy and Cogburn 2001).

The Patagonian steppe of Argentina is considered the fourth largest desert in the world by area; it is limited to the west by the Andean Mountains that constitutes a natural barrier to the humid Westerlies, the prevailing winds from southern Pacific Ocean. In northwestern Patagonia, forests occupy a humid narrow area along the Andean Mountains, separated of the arid steppe by a transitional (ecotonal) zone, where most regional development efforts are concentrated. The driest portion of this ecotone is a semiarid shrub-grass steppe affected by overgrazing and wildfires (Oddi et al. 2013). The climate is characterized by cold and humid winters and very dry summers, and the soils are coarse textured, very poor in organic C, of low water retention and high risk of erosion (Ayesa et al. 2002). Since in this region no studies on the effects of organic amendments on soil restoration were available, we installed a field experiment in a degraded, burned site, with urban composts (biosolids and organic fraction of municipal solid waste) applied only once at the beginning of the experiment. In previous works, we reported chemical and biological changes during 3 years after compost application, which consisted mainly in an increase in soil organic C, total nitrogen (N), microbial activity and aboveground phytomass (Kowaljow and Mazzarino 2007; Kowaljow et al. 2010). The objectives of the present work were (1) to evaluate the effects of compost addition on plant available water, soil moisture and soil temperature over 3 years, and (2) to relate plant available water and soil moisture with bulk density, soil organic C, N and phosphorous (P) availability, and aboveground phytomass. To further investigate the effect of plant water consumption, an experiment with excised vegetation and watering was conducted. We hypothesized that composts would be slowly incorporated into the soil resulting in increased organic C and nutrient and water availability over time, while soil temperature and bulk density would decrease; however, greater vegetation growth would result in no changes in soil moisture.

Materials and methods

Field experiments and response variables

A long-term experiment was installed in November 2004 in an overgrazed pasture that had been burned by a wildfire 10 months before. The study site is located in NW Patagonia (40°34′24″S, 70°49′57″W) at 720 m a.s.l., and has a 4.1% SW-oriented slope. Mean annual temperature and precipitation are 11.5 °C and 300 mm, respectively; precipitations are concentrated in the period between May and August (autumn–winter in the southern hemisphere); soils are Xeropsamments (Kowaljow and Mazzarino 2007).

The experiment consisted in four blocks ($n = 4$), each block having five plots of 66 m^2 (Randomized Complete Block Design); blocks were separated by 5 m buffer strips and plots within blocks by 2 m strips; domestic herbivores were excluded. Composts of different origin and post-composting treatment were used: biosolids compost (BC) and compost of the organic fraction of municipal solid waste (MC), which were either unscreened (BCns, MCns) or screened through a 5-mm mesh (BCs, MCs). Then, five treatments were applied: four types of composts and a control without compost (C), each replicated four times. All composts were surface applied at a rate of 40 Mg ha^{-1} (dry weight) at the beginning of the study; there were no additional applications. The soil has a sandy texture (93% of sand, 4% of silt and 3% of clay), and after the wildfire, main characteristics were as follows: 14.1% volumetric soil moisture at field capacity and 11.1% at wilting point, 6.6 of pH, 6.0 g kg^{-1} organic C, 0.5 g kg^{-1} N, and 4.8, 3.1, and 2.3 cmol kg^{-1} of exchangeable Ca, Mg and K, respectively. BC was obtained by co-composting biosolids (15% solid content) with wood shavings and yard trimmings (1:1.5 ratio, v/v) in the Biosolids Composting Plant of Bariloche city, and MC by composting on-site separated organic domestic waste, yard trimmings and grass clippings in the waste treatment facility of Villa La Angostura city. BC was richer in organic matter and nutrients than MC while this had higher values of pH and divalent cations; in both composts, the highest values of organic C corresponded to the unscreened ones (Table 1 and Table S1 of Supplementary Material).

Soils were sampled for chemical analyses at 0–10 cm depth, one and 2 years after compost application (November 2005 and November 2006). Five randomly collected subsamples were thoroughly mixed to yield one composite sample per plot. Compost particles that remained on the soil surface were removed before sampling. For extractable P, air-dried soil, ground to pass a 2-mm mesh was employed; P was determined in 0.5 M $NaHCO_3$ extracts (1:20 soil:solution ratio) by the molybdate-ascorbic acid blue method. Soil organic C was analyzed in finely ground samples (sieved by 0.5-mm mesh) by wet-digestion (Walkley–Black). Inorganic nitrogen ($Ni = NO_3^- + NH_4^+$) and potential net N mineralization were evaluated in field moist samples, sieved by 2-mm mesh. Inorganic nitrogen was determined in 2 M KCl extracts (1:5 soil:solution ratio), nitrates by the copperized cadmium reduction and ammonium by the Berthelot reaction (Page et al. 1982). Potential N mineralization was assessed in laboratory incubations under controlled conditions; soil samples (100 g) were incubated in plastic jars (0.25 L) during 16 weeks, and mineralization rates were estimated as Ni at t16 minus Ni at t0 (Kowaljow and Mazzarino 2007).

After 1, 2 and 4 years after compost addition, field capacity (FC) and permanent wilting point (PWP) were measured using a pressure membrane and a pressure plate apparatus (developed primarily by Richards 1947). For this, air-dried soils, sieved through 2-mm mesh, were employed (Topp and Ferré 2002); one composite soil sample (of five subsamples) was taken from each plot (0–10 cm depth); as for chemical analyses, surface compost deposits were removed before sampling. Plant available water (PAW) was calculated as the difference between FC and PWP.

Immediately after compost application and during three years, volumetric soil moisture (0–15 cm) was monthly or bimonthly measured with a handheld time-domain reflectometer (TDR, TRIME-FM3, Imko GmbH, Ettlingen, Germany). Soil temperature was measured at the same dates at 7 cm depth using digital thermometers. All measurements were taken in three points per plot randomly distributed. Soil bulk density (BD) was determined in the topsoil (0–5 cm) by the core method only once 3 years of compost application.

The aboveground phytomass of herbaceous plants was assessed 2 years after compost application (November 2006) by clipping the vegetation at ground level in

Table 1 Chemical properties of biosolids and municipal solid waste composts

	Biosolids composts		Municipal composts	
	Screened BCs	Unscreened BCns	Screened MCs	Unscreened MCns
pH	5.6 (0.03)	5.4 (0.05)	7.8 (0.01)	7.6 (0.06)
EC (dS m^{-1})	0.60 (0.02)	1.23 (0.05)	0.45 (0.12)	0.27 (0.12)
Total elements (g kg^{-1})				
Organic C	215 (7.5)	282 (9.3)	128 (4.4)	151 (5.1)
N	15.7 (0.7)	18.4 (0.1)	7.7 (0.1)	7.0 (0.9)
Ca	12.4 (0.2)	13.7 (0.1)	49.1 (3.4)	40.4 (6.3)
Mg	2.7 (0.09)	2.6 (0.01)	6.1 (0.17)	5.1 (0.18)
K	1.7 (0.01)	1.9 (0.01)	1.5 (0.06)	1.3 (0.29)
P	5.2 (0.4)	5.6 (0.4)	4.1 (0.18)	3.4 (0.3)
Olsen-P (mg kg^{-1})	1286 (34.7)	1677 (90.8)	155 (17.6)	153 (26.6)

Values are means with standard deviation in brackets (data of median, minima and maxima, and skewness coefficients are given in Table S1 of Supplementary Material)

EC electrical conductivity. Treatment codes: *C* control, *BCs* screened biosolids compost, *BCns* unscreened biosolids compost, *MCs* screened municipal compost, *MCns* unscreened municipal compost

Table 2 Soil organic C, extractable P, inorganic N and potential mineralized N after 1 and 2 years of compost applications

	Organic C ($g\ kg^{-1}$)		Extractable P ($mg\ kg^{-1}$)		Inorganic N ($mg\ kg^{-1}$)		Pot. min. N ($mg\ kg^{-1}$)	
	1 year	2 year	1 year	2 year	1 year	2 year	1 year	2 year
C	5.7 b	5.5 b	11.4 b	9.0 d	3.5 a	2.5 ab	18.9 b	17.8 b
	(1.3)	(0.8)	(1.9)	(2.3)	(0.8)	(1.1)	(4.5)	(6.2)
BCs	10.0 a	7.0 a	36.7 a	36.3 a	8.7 a	3.3 a	29.1 a	28.2 a
	(2.8)	(0.3)	(3.7)	(5.0)	(5.0)	(1.3)	(7.4)	(4.6)
BCns	9.2 a	7.0 a	37.8 a	26.9 ab	4.8 a	1.3 bc	26.7 a	28.3 a
	(2.5)	(0.5)	(3.3)	(10.6)	(3.7)	(0.4)	(2.8)	(1.5)
MCs	8.2 a	7.1 a	17.1 b	15.1 cd	4.5 a	2.1 ab	31.1 a	27.7 a
	(1.0)	(0.7)	(2.4)	(2.4)	(2.9)	(1.2)	(5.8)	(4.2)
MCns	7.1 a	6.8 a	15.3 b	19.6 bc	2.3 a	0.7 c	28.3 a	27.0 a
	(0.9)	(0.9)	(3.8)	(10.9)	(1.0)	(0.1)	(6.1)	(5.1)
Treatment effect (*p* value)	<0.001	0.016	<0.001	<0.001	0.110	0.005	0.035	0.004
Block effect (*p* value)	<0.001	0.182	0.387	0.095	0.391	0.070	0.819	0.016

Values are means with SD in brackets. Different letters indicate significant differences among treatments ($p < 0.05$). Treatment codes as in Table 1

Table 3 Bulk density measured after 3 years of compost applications and plant available water measured after 1, 2 and 4 years of compost application

	Bulk density ($g\ cm^{-3}$)	Plant available water (%)		
		Time (years)		
		1	2	4
C	1.20 c	4.2	3.7	3.1
	(0.11)	(2.5)	(0.7)	(0.3)
BCs	1.01 ab	6.4	3.6	3.6
	(0.19)	(3.0)	(1.3)	(0.5)
BCns	0.89 a	3.3	2.2	4.4
	(0.15)	(0.9)	(1.2)	(1.2)
MCs	1.14 bc	3.9	3.8	5.3
	(0.11)	(0.7)	(1.8)	(2.6)
MCns	1.15 bc	4.6	3.4	4.2
	(0.14)	(2.1)	(0.4)	(0.8)
Treatment effect (*p* value)	<0.001	ns	ns	ns
Block effect (*p* value)	<0.001	ns	ns	ns

Values are means with SD in brackets. Different letters indicate significant differences among treatments ($p < 0.05$). *ns* nonsignificant differences. Treatment codes as in Table 1

randomly placed quadrats of 50 cm × 50 cm (three samples per plot); samples were oven-dried at 60 °C for 48 h and weighed.

To evaluate the effect of vegetation on soil moisture, a plant removal experiment was conducted: 3 years after compost application, plant aboveground phytomass was excised at soil level in three treatments (C, BCns and MCns) using three squares (0.25 m^2) per plot. Each square was watered to simulate a low-intensity rainfall (10 mm in 1 h). At 1, 24, 48 and 192 h after the irrigation, soil moisture (0–15 cm) was determined with the above-mentioned TDR.

Statistical analyses

Differences among treatments were evaluated using one-way blocked ANOVA, considering both, treatment and block effects, as fixed (Di Rienzo et al. 2013). When residuals did not present normal distribution, a log transformation to data was applied, and when presented heterogeneous variance general linear mixed models (GLM) were used, and their fit evaluated using the Akaike information criterion (Burnham and Anderson 2002). Multiple comparisons were performed using Fisher's least significant difference (LSD). In all cases, differences were

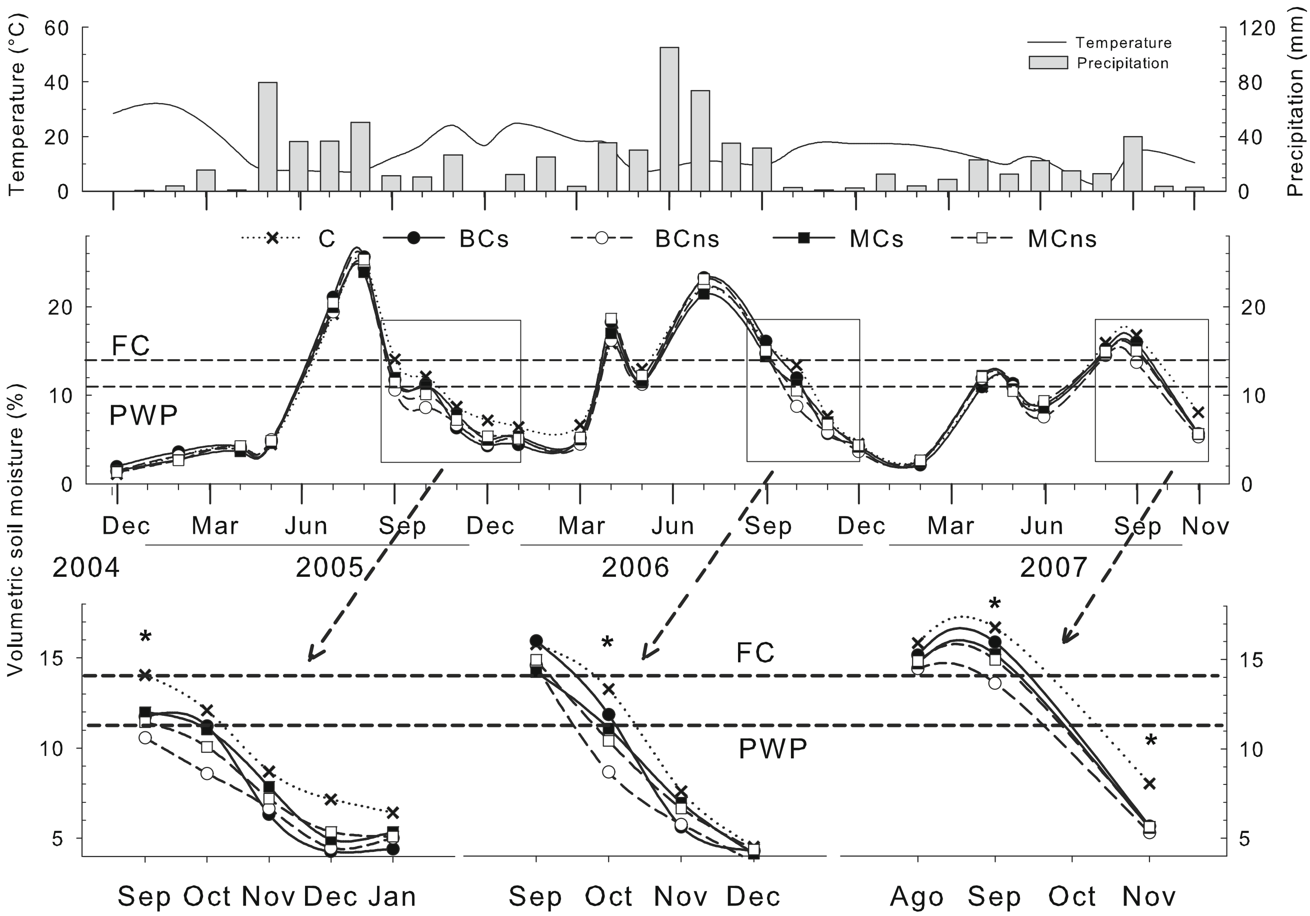

Fig. 1 Monthly precipitation and temperature (*upper*) and soil moisture (*middle*) during 3 years of experiment. In the *bottom*, details of the drying period of each year are given; *asterisks* indicate significant differences among treatments ($p < 0.05$). Treatment codes: *C* control, *BCs* screened biosolids compost, *BCns* unscreened biosolids compost, *MCs* screened municipal compost, *MCns* unscreened municipal compost

considered statistically significant at the 0.05 probability level. To explore the effect of soil bulk density, soil organic C and aboveground phytomass on plant available water and soil water content, simple linear regression analyses were performed. In all cases, the Infostat v. 2011 Statistical Package was employed (Di Rienzo et al. 2013).

Results

Soil organic C and potential mineralized N increased significantly with compost addition in all treatments and both sampling dates (Table 2). Soil extractable P also increased with compost addition, but the magnitude of the increase was dependant on compost type, being higher in BC treatments than in MC treatments. Inorganic N did not change with respect to the control (Table 2). Soil bulk density was significantly lower in the BC treatments (16 and 26% for BCs and BCns, respectively) than in the control, but only BCns differed significantly from both MC treatments (Table 3).

Despite differences in soil organic C and bulk density, PAW values were very low and no differences were observed among treatments at any date (Table 3). Values of FC varied between 8.9 and 14.1%, and those of PWP between 6.2 and 7.7%; PWP showed some differences among treatments over the years, but no clear trends (data not shown).

During the 3 years of soil moisture measurements (2004–2007), mean annual air temperature ranged from 9.6 to 10.9 °C with a mean monthly maximum of 21.6 °C in February 2005, and a mean monthly minimum of 2.4 °C in August 2005 (Fig. 1). Annual precipitation was very variable: 254 mm in 2005, 392 mm in 2006 and 158 mm in 2007 (Fig. 1). There were seasonal fluctuations in soil moisture directly related to precipitation, which was higher in winter and lower in summer (Fig. 1). Soil temperature did not change with compost application, and varied between 2 and 17 °C in autumn–winter and 13–36 °C in spring–summer (data not shown).

There was a significant increase in aboveground phytomass in both BC treatments and the MCns treatment

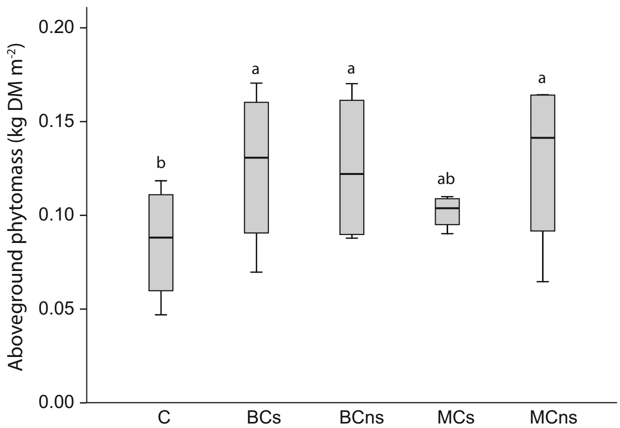

Fig. 2 Compost effects on aboveground phytomass after 2 years of compost application. *Different letters* indicate significant differences for the same column ($p < 0.05$). Treatment codes as in Fig. 1

(treatment effect $p = 0.029$; block effect $p < 0.001$) (Fig. 2). However, composts did not increase soil moisture with respect to the control. On the contrary, when significant differences among treatments occurred, the highest moisture contents corresponded to the control (Fig. 1; Table 4). These differences were only observed during the soil drying periods, i.e., between September and November of every year, corresponding to the spring months (Fig. 1). When the effect of plants was removed in the experiment with excised vegetation, no differences of soil moisture between the control, and the considered amended treatments (BCns and MCns) were found (Fig. 3).

Simple regressions analyses showed that bulk density was not related with either plant available water or soil moisture during the soil drying periods (data not shown). The increase in soil organic carbon after 2 years of experiment installation was significantly related with the decrease in soil water content during the soil drying periods (Fig. 4). Similar results were observed between the aboveground phytomass measured after 2 years of experiment installation and the soil water content during the soil drying periods (Fig. 5).

Discussion

Soil bulk density and SOM clearly changed with compost addition, especially in the treatment amended with unscreened biosolids compost, which still had visible residual organic materials on the surface after 4 years of application. However, there was no change in plant available water in the compost treatments. This could be due to the relatively low dose of compost application (40 Mg kg^{-1}) and to the coarse soil texture that hinders soil aggregation. Duong et al. (2012) pointed out that organic amendments improve aggregate stability directly by binding of clay and indirectly by increasing microbial activity and the production of binding agents; however, they found that in sandy soils with less than 13% clay such improvements are not possible. In this type of soils, changes of PAW were observed with very high doses (540 Mg ha^{-1}) that especially increased soil field capacity (Curtis and Claassen 2009). With lower doses of composts, such as in our study, Weber et al. (2007) found short-term effects on PAW (1 and 5 months after compost application) that disappear thereafter. Other authors found significant effects of composts on several physical properties of coarse-textured soils (bulk density, porosity, infiltration rates, saturated hydraulic conductivity), but no effects on soil water retention (Leroy et al. 2008; Arthur et al. 2011).

In sandy soils of Mediterranean climate, Martínez et al. (2003) found a significant decrease in runoff and soil losses

Table 4 Soil water content in months with significant differences among treatments

	Soil water content (%)			
	Sep-05	Oct-06	Sep-07	Nov-07
C	14.1 a	13.4 a	16.8 a	8.1 a
	(3.5)	(4.0)	(1.8)	(2.4)
BCs	11.7 b	12.0 ab	16.0 abc	5.7 b
	(3.6)	(3.0)	(0.5)	(0.9)
BCns	10.6 b	8,7 c	13.7 d	5.3 b
	(3.0)	(1.0)	(2.7)	(0.8)
MCs	12.0 b	11.2 b	15.3 bcd	5.6 b
	(3.8)	(2.7)	(1.2)	(0.4)
MCns	11.4 b	10.5 bc	15.0 cd	5.6 b
	(3.2)	(1.7)	(1.5)	(0.9)
Treatment effect (p value)	0.017	0.006	0.038	0.032
Block effect (p value)	<0.001	<0.001	0.011	0.176

Values are means with SD in brackets. Different letters indicate significant differences among treatments ($p < 0.05$). Treatment codes as in Table 1

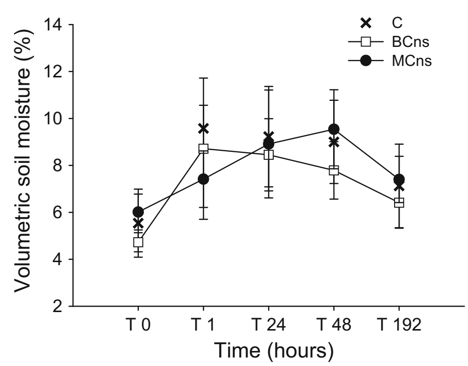

Fig. 3 Soil moisture evolution in excised vegetation quadrats after irrigation. No significant differences were found among treatments for any date. Treatment codes as in Fig. 1

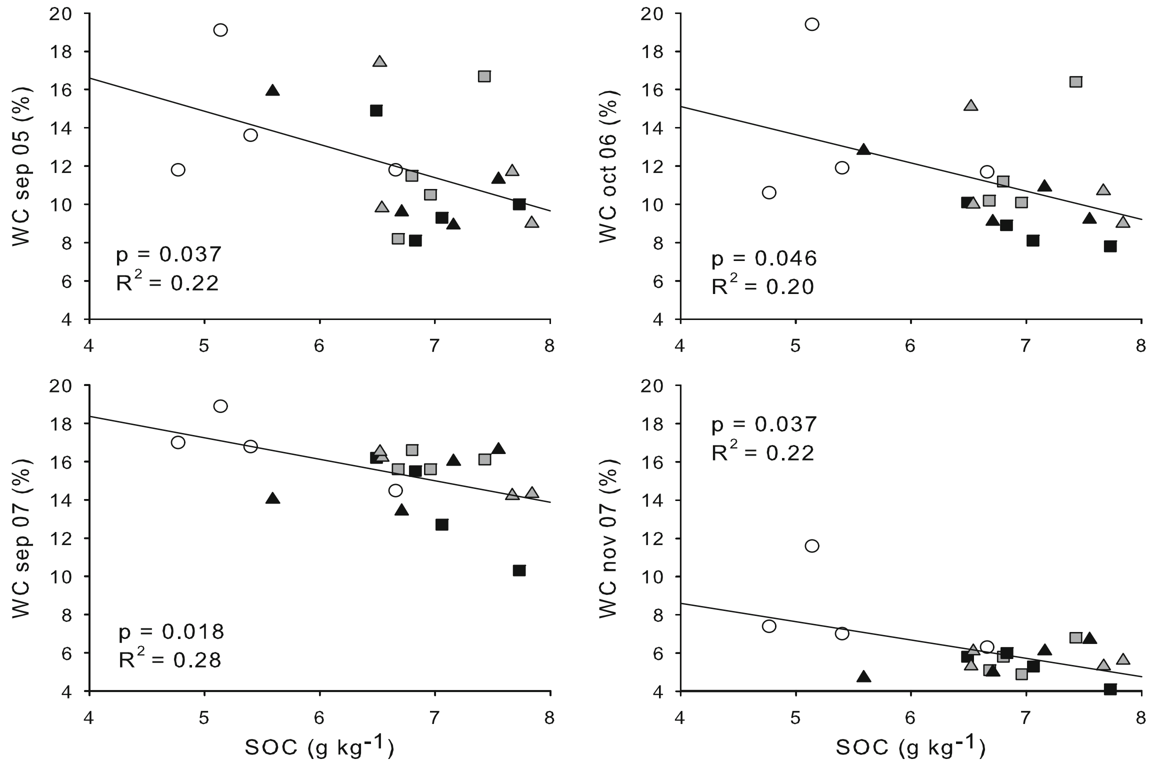

Fig. 4 Simple linear regression analysis between soil organic carbon (SOC) 2 years after compost application and soil water content (WC) during months with significant differences among treatments. Controls *open circles*, BCs *gray squares*, BCns *black squares*, MCs *gray triangles*, MCns *black triangles*

after 3 and 4 years of a single application of biosolids compost and municipal solid waste compost at a dose that doubled ours. These authors suggested that this was a consequence of a complex process in which plant cover and the role of SOM in the formation of aggregates are the major factors involved. Even at a lower dose of biosolids compost (27 Mg ha^{-1}) applied every third year, Aranyos et al. (2016) also found a significant improvement of water infiltration in a sandy soil, reducing runoff and water erosion under simulated high-intensity rainfall; these effects lasted only 2 years and were strongly related with SOM dynamics.

Amendment doses will depend not only on the main goal of the application (fertilization, restoration or remediation), but also on factors like climate, soil type, amendment quality and contamination risk (Curtis and Claassen 2009; Leon et al. 2012; Jorge-Mardomingo et al. 2015). Furthermore, to carry and apply organic amendments to the field are expensive activities that can hinder high application rates (Reeve et al. 2012; Zemánek et al. 2012). Results of the present experiment reported previously showed that the applied dose not only increased SOM, nutrients, microbial activity and plant biomass in the short-term (Kowaljow and Mazzarino 2007; Kowaljow et al. 2010), but also had significant effects on chemical and biochemical soil properties after 6 years, especially with biosolids compost (Gonzalez Polo et al. 2015).

Despite increasing SOM, this dose was not enough to increase soil moisture. Moreover, during the vegetative growth period of the dominant vegetation that coincides with decreasing precipitation, i.e., from September to November (spring in the southern hemisphere), soil moisture values were lower in the compost treatments than in the control, suggesting that compost application contributed to a higher use of soil water by plants. Higher phytomass in these treatments possibly increased the consumption of water due to higher transpiration and the ability to explore more soil volume, thus, improving the use of a soil water portion that plants of the control treatment could not use. In concordance, other studies in our region indicated higher soil moisture in degraded areas of low vegetation cover than in well preserved areas of high plant cover associated to high water consumption (Bisigato and Lopez Laphitz 2009). The plant removal experiment showed that there were no differences in soil moisture among treatments when vegetation was not present, partially supporting the idea that soil moisture changes were related to the water consumption by plants. Similarly, in a sandy soil of arid productive lands amended with composts, higher plant biomass and lower soil moisture during the period of diminishing precipitation were found in

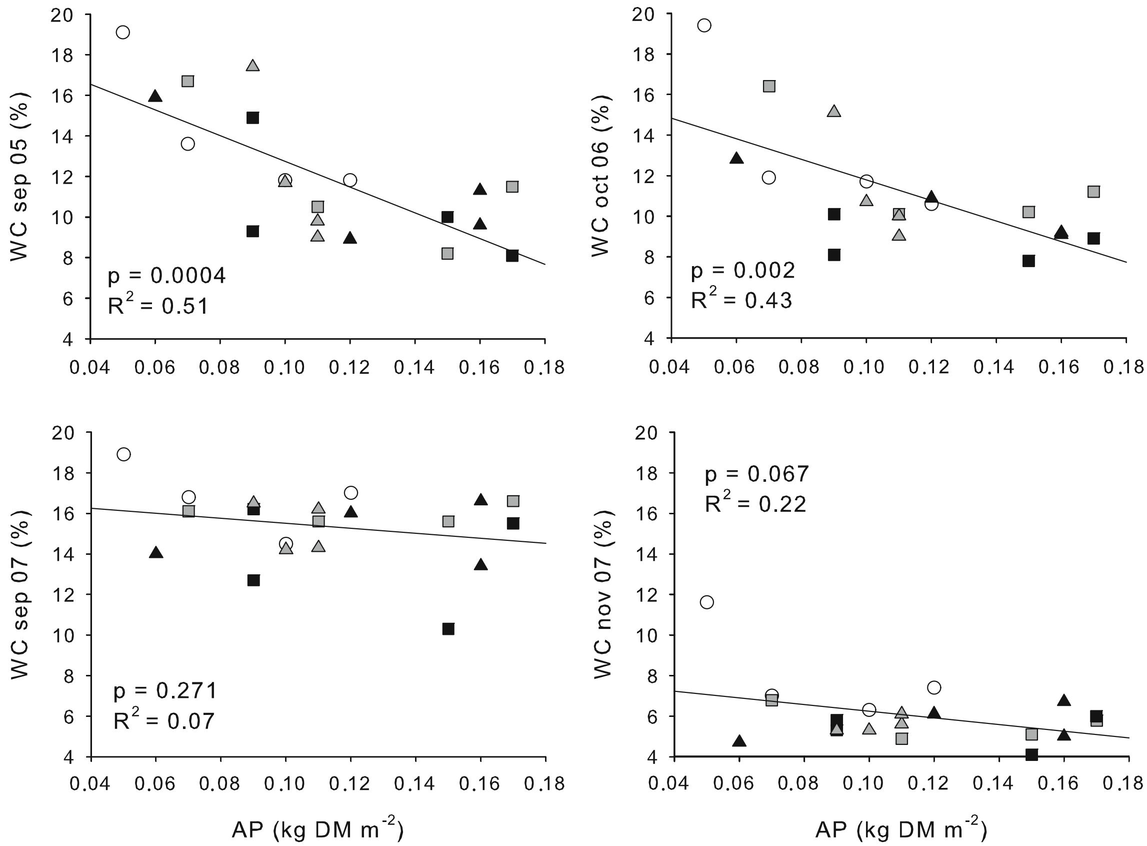

Fig. 5 Simple linear regression analysis between aboveground phytomass (AP) 2 years after compost application and soil water content in months with significant differences among treatments. Controls *open circles*, BCs *gray squares*, BCns *black squares*, MCs *gray triangles*, MCns *black triangles*

amended plots with respect to the control (Affholder 1995). This author suggested that compost applications could limit grain production when the crop water demand exceeds the soil water supply in amended plots.

In summary, in sandy soils of semiarid Patagonia, a single compost application of 40 Mg ha^{-1} was not enough to increase plant available water despite significantly increasing soil organic C and aboveground phytomass. Water and N are considered the main controls of plant productivity in arid ecosystems, and they interact with each other (West and Skujins 1978; Mazzarino et al. 1998; Yahdjian et al. 2011). While no changes in inorganic N concentrations were observed at both measured dates, the increase in potential mineralized N in the amended soils indicated that during moist periods (and adequate temperatures), N uptake was increased, enhancing plant growth. Although the applied composts did not change soil water constants, they increased plant available nutrients and improved the use of available water during the crucial spring months, i.e., plant biomass increased in the amended treatments and used water that was also available for vegetation in the control plots but not used due to nutrient limitation (available water was then prone to be lost by evaporation in these plots). A negative effect of higher nutrient availability during very dry years, as suggested by Affholder (1995) for crop production, cannot be discarded. However, in arid ecosystems a better response of native vegetation to soil nutrient enrichment could be expected since they are adapted to frequent disturbances such as wildfires that can temporarily increase nutrient availability.

Conclusions

Improving soil structure with organic additions is limited in sandy soils because organic matter is prone to rapid decomposition, the buildup of aggregates is minimal, and the binding effect is transient. In arid ecosystems, organic matter decomposition is slowed down by the unfavorable climatic conditions, but its incorporation into the soil also occurs more slowly; consequently, the effect of organic amendments on water availability depends markedly on the applied dose or the frequency of application in order to maintain adequate SOM levels. Nevertheless, the increase in microbial activity and available nutrients with a single application of organic amendments can favor biomass production and a more efficient use of soil water.

In the present work, a single application of two types of urban composts increased SOM and nutrient availability in a sandy soil of xeric moisture regime in NW Patagonia, but was insufficient to improve plant available water. Enhanced plant growth and water consumption due to increased N availability in amended treatments resulted in lower soil moisture than in non-amended plots. This was especially evident during the vegetative growth period of the dominant vegetation that coincides with decreasing precipitation. This highlights the fact that a portion of soil water is not being used by plants in non-amended plots due to nutrient constraints. Results indicate that a relatively high dose of compost application (compared to usual agronomic rates) of 40 Mg ha^{-1} in this arid ecosystem contributed to increase plant available nutrients and improved the use of available water during the crucial spring months.

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References

Affholder F (1995) Effect of organic matter input on the water balance and yield of millet under tropical dryland condition. Field Crop Res 41:109–121. doi:10.1016/0378-4290(94)00115-S

Aranyos JT, Tomócsik A, Makádi M, Mészáros J, Blaskó L (2016) Changes in physical properties of sandy soil after long-term compost treatment. Int Agrophys 30:269–274. doi:10.1515/intag-2016-0003

Arthur E, Cornelis WM, Vermang J, De Rocker E (2011) Amending a loamy sand with three compost types. Soil Use Manag 27:116–123. doi:10.1111/j.1475-2743.2010.00319.x

Ayesa JA, López CR, Bran DE, Umaña FJ, Lagorio PA (2002) Cartografía biofísica de la Patagonia Norte. INTA Estación Experimental Agropecuaria Bariloche, PAN, PRODESAR

Bastida F, Kandeler E, Hernández T, García C (2008) Long-term effect of municipal solid waste amendment on microbial abundance and humus-associated enzyme activities under semi-arid conditions. Microb Ecol 55:651–661. doi:10.1007/s00248-007-9308-0

Bisigato AJ, Lopez Laphitz RM (2009) Ecohydrological effects of grazing-induced degradation in the Patagonian Monte, Argentina. Austral Ecol 34:545–557. doi:10.1111/j.1442-9993.2009.01958.x

Burnham KP, Anderson DR (2002) Model selection and inference: a practical information-theoretic approach, 2nd edn. Springer, Berlin

Castán E, Satti P, Gonzalez-Polo M, Iglesias MC, Mazzarino MJ (2016) Managing the value of composts as organic amendments and fertilizers in sandy soils. Agric Ecosyst Environ 224:29–38. doi:10.1016/j.agee.2016.03.016

Cheng L, Lu Q, Wu B, Yin C, Bao Y, Gong L (2016) Estimation of the costs of desertification in China: a critical review. Land Degrad Dev. doi:10.1002/ldr.2562

Clapp EC (2007) Organic wastes in soils: biogeochemical and environmental aspects. Soil Biol Biochem 39:1239–1243. doi:10.1016/j.soilbio.2006.12.001

Cooke RU, Warren A, Goudie AS (1993) Desert geomorphology. UCL Press, London, p 526

Curtis MJ, Claassen VP (2009) Regenerating topsoil functionality in four drastically disturbed soil types by compost incorporation. Restor Ecol 17:24–32. doi:10.1111/j.1526-100X.2007.00329.x

Di Rienzo JA, Casanoves F, Balzarini MG, Gonzalez L, Tablada M, Robledo CW (2013) InfoStat, versión 2013. Grupo InfoStat, FCA, Universidad Nacional de Córdoba. http://www.infostat.com.ar

Duong TTT, Penfold C, Marschner P (2012) Differential effects of composts on properties of soils with different textures. Biol Fertil Soil 48:699–707. doi:10.1007/s00374-012-0667-4

Feller C, Bernhard-Reversat F, Garcia JL, Pantier JJ, Roussos S, Vanvliet-Lanoe B (1983) Etude de la matière organique de différentes fractions granulométriques d'un sol sableux tropical. Effet d'un amendement organique (compost). Cah. ORSTOM, Ser Pedól 20:223–238

Gabrielle B, Da-Silveira J, Houot S, Francou C (2004) Simulating urban waste compost effects on carbon and nitrogen dynamics using a biochemical index. J Environ Qual 33:2333–2342. doi:10.2134/jeq2004.2333

García Navarro FJ, Amorós Ortiz-Villajos JA, Sánchez Jiménez CJ, Bravo Martín-Consuegra S, Márquez Cubero E, Jiménez Ballesta R (2009) Application of sugar foam to red soils in a semiarid Mediterranean environment. Environ Earth Sci 59:603–611. doi:10.1007/s12665-009-0058-9

Garcia-Orenes F, Guerrero C, Mataix-Solera J, Navarro-Pedreno J, Gomez I, Mataix-Beneyto J (2005) Factors controlling the aggregate stability and bulk density in two different degraded soils amended with biosolids. Soil Tillage Res 82:65–76. doi:10.1016/j.still.2004.06.004

Gonzalez Polo M, Kowaljow E, Castán E, Sauzet O, Mazzarino MJ (2015) Persistent effect of organic matter pulse on a sandy soil of semiarid Patagonia. Biol Fertil Soils 51:241–249. doi:10.1007/s00374-014-0961-4

Hudson BD (1994) Soil organic matter and available water capacity. J Soil Water Conserv 49:189–194

Jorge-Mardomingo I, Jiménez-Hernández ME, Moreno L, de la Losa A, de la Cruz MT, Casermeiro MA (2015) Application of high doses of organic amendments in a Mediterranean agricultural soil: an approach for assessing the risk of groundwater contamination. Catena 13:74–83. doi:10.1016/j.catena.2015.03.013

Khaleel R, Reddy KR, Overcash MR (1981) Changes in soil physical properties due to organic waste applications: a review. J Environ Qual 10:133–141. doi:10.2134/jeq1981.00472425001000020002x

Kowaljow E, Mazzarino MJ (2007) Soil restoration in semiarid Patagonia: chemical and biological response to different compost quality. Soil Biol Biochem 39:1580–1588. doi:10.1016/j.soilbio.2007.01.008

Kowaljow E, Mazzarino MJ, Satti P, Jiménez-Rodríguez C (2010) Organic and inorganic fertilizer effects on a degraded Patagonian rangeland. Plant Soil 332:135–145. doi:10.1007/s11104-009-0279-4

Leon A, Kohyama K, Mishima S, Ohkura T, Shirato Y, Takata Y, Taniyama I, Obara H (2012) Factors controlling organic amendment application rate and long-term change in application rate in Japanese paddy field using longitudinal questionnaire survey dataset (the Basic Soil Environment Monitoring Project,

Stationary Monitoring, 1979–1998). Soil Sci Plant Nutr 58:104–120. doi:10.1080/00380768.2012.655675
Leroy BLM, Herath HMSK, De Neve S, Gabriels D, Bommele L, Reheul D, Moens M (2008) Effect of vegetable, fruit and garden (VFG) waste compost on soil physical properties. Compost Sci Util 16:43–51. doi:10.1080/1065657X.2008.10702354
Martínez F, Casermeiro MA, Morales D, Cuevas G, Walter I (2003) Effects on runoff quantity and quality of urban organic wastes applied in a degraded semiarid ecosystem. Sci Total Environ 305:12–21. doi:10.1016/S0048-9697(02)00472-2
Mazzarino MJ, Bertiller M, Sain CL, Satti P, Coronato F (1998) Soil nitrogen dynamics in northeastern Patagonia steppe under different precipitation regimes. Plant Soil 202:125–131. doi:10.1023/A:1004389011473
McCoy S, Cogburn B (2001) Composting manure for value-added products. BioCycle, Emmaus
Oddi FJ, Ghermandi L, Lasaponara R (2013) Annual burned area across a precipitation gradient in northwestern Patagonia steppe, vol 15. EGU General Assembly, Vienna
Page A, Miller RH, Keeney D (1982) Methods of soil analysis. In: Methods of soil analysis, part 2, 2nd edn. Series Agronomy No. 9. ASA, SSSA, Madison, pp 1159
Reeve JR, Endelman JB, Miller BE, Hole DJ (2012) Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. Soil Sci Soc Am J 76:278–285. doi:10.2136/sssaj2011.0123
Reynolds JF, Smith DMS, Lambin EF, Turner BL, Mortimore M, Batterbury SP, Downing TE, Dowlatabadi H, Fernández RJ, Herrick JE, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre FT, Ayarza M, Walker B (2007) Global desertification: building a science for dryland development. Science 326:847–851. doi:10.1126/science.1131634
Richards LA (1947) Pressure membrane apparatus, construction and use. Agric Eng 28:451–460
Ryals R, Kaiser M, Torn S, Berhe AA, Silver WL (2014) Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. Soil Biol Biochem 68:52–61. doi:10.1016/j.soilbio.2013.09.011
Rynk R, van der Kamp M, Willson GB, Singley ME, Richard TL, Kolega JJ, Gouin FR, Laliberty L, Kay D Jr, Murphy DW, Hoitink HA, Brinton WF (1992) On-farm composting handbook. Northeast Regional Agricultural Engineering Service, Cooperative Extension Service, Ithaca
Srivastava V, de Araujo ASF, Vaish B, Bartelt-Hunt S, Singh P, Singh RP (2016) Biological response of using municipal solid waste compost in agriculture as fertilizer supplement. Rev Environ Sci Biotechnol. doi:10.1007/s11157-016-9407-9
Suzuki S, Noble AD, Ruaysoongnern S, Chinabut N (2007) Improvement in water-holding capacity and structural stability of a sandy soil in northeast Thailand. Arid Land Res Manag 21:37–49. doi:10.1080/15324980601087430
Topp GC, Ferré PA (2002) The soil solution phase. In: Dane JH, Topp GC (eds) Methods of soil analysis, part 4 physical analysis. Soil Science Society of America Inc, Madison, pp 417–1071
Uzoma KC, Inoue M, Andry H, Fujimaki H, Zahoor Z, Nishihara E (2011) Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manag 27:205–212. doi:10.1111/j.1475-2743.2011.00340.x
Vieira RMSP, Tomasella J, Alvalá RCS, Sestini MF, Affonso AG, Rodriguez DA, Barbosa AA, Cunha APMA, Valles GF, Crepani E, De Oliveira SBP, De Souza MSB, Calil PM, De Carvalho MA, Valeriano DM, Campello FCB, Santana MO (2015) Identifying areas susceptible to desertification in the Brazilian northeast. Solid Earth 6:347–360. doi:10.5194/se-6-347-2015
Walter I, Martínez F, Cuevas G (2006) Biosolid amendment of a calcareous, degraded soil in a semi-arid environment I. Span J Agric Res 4:47–54. doi:10.5424/sjar/2006041-177
Weber J, Karczewska A, Drozd J, Licznar M, Licznar S, Jamroz E, Kocowicz A (2007) Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol Biochem 39:1294–1302. doi:10.1016/j.soilbio.2006.12.005
West NE, Skujins J (1978) Nitrogen in desert ecosystems, US/IBP synthesis series 9. Dowden Hutchinson and Ross, Stroudsburg
Wortmann CS, Shapiro CA (2008) The effects of manure application on soil aggregation. Nutr Cycl Agroecosyst 80:173–180. doi:10.1007/s10705-007-9130-6
Yahdjian L, Gherardi L, Sala OE (2011) Nitrogen limitation in arid-subhumid ecosystems: a meta-analysis of fertilization studies. J Arid Environ 75:675–680. doi:10.1016/j.jaridenv.2011.03.003
Zemánek P, Burg P, Jelínek A (2012) The cost efficiency of higher doses of compost application. Acta Univ Agric Silvic Mendel Brun 60:253–258. doi:10.11118/actaun201260080253