

RESEARCH ARTICLE

Mid-term effects on ecosystem services of quarry restoration with Technosols under Mediterranean conditions: 10-year impacts on soil organic carbon and vegetation development

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The use of Technosols for the restoration of limestone quarries overcomes the usual “in situ” scarcity of soil and/or its poor quality. The use of mine spoils, improved with mineral and/or organic amendments, could be an efficient and environmentally friendly option. Properly treated sewage sludge from urban wastewater treatment plants could be a suitable organic amendment and fertilizer (rich in N and P) whenever its pollutant burden is low (heavy metals and/or organic pollutants). Its appropriate use could improve essential soil physical and chemical properties and, therefore, promote key ecosystem services of restored areas, such as biomass production and carbon sequestration, as well as biodiversity and landscape recovery. However, the mid-term impacts of these restoration practices on soil functioning and their services have rarely been reported in the available literature. In this study we assess the mid-term effects (10 years) of the use of sewage sludge as a Technosol amendment on soil organic carbon (SOC), nutrient status, and plant development in several restored quarries. Soils restored using sewage sludge showed a threefold increase in SOC compared to the corresponding unamended ones, despite the moderate sludge dosage applied (below 50 tonnes/ha). Plant cover was also higher in amended soils, and recruitment was not affected by sludge amendment at these doses. This study demonstrates that, used at an appropriate rate, sewage sludge is a good alternative for the valorization of mine spoils in quarry restoration, improving some important regulatory ecosystem services such as carbon sequestration, without compromising woody plant encroachment.

Key words: organic amendments, quarry restoration, sewage sludge, soil organic carbon sequestration, Technosol

Implications for Practice

- The use of sewage sludge as organic amendment in mine spoil-based Technosols is an environmentally friendly and economically suitable option for the restoration of land degraded by quarrying and could allow a fast recovery of the ecosystem services lost.
- After 10 years, sludge-amended Technosols boosted primary production and promoted a threefold increase in organic carbon stocks without compromising woody plant encroachment.
- The use of digested municipal sewage sludge with a high degree of stability (>30%), at moderate doses (ca. 45 tonnes/ha), in Technosol construction minimizes environmental risks and maximizes ecosystem services in terms of carbon sequestration and plant biodiversity.

depleted (Moreno-Peñaranda et al. 2004). Manufactured soils (Technosols) could be a viable soil source when the availability of suitable natural soils is limited (Watkinson et al. 2017), with this technology being emblematic of the issues we face for the management of the soils of the Anthropocene (Leguédouis et al. 2016). The use of organic waste for Technosol construction is a widely used practice in mine restoration (Asensio et al. 2013; Lomaglio et al. 2017; Watkinson et al. 2017), with the aim of speeding up the biological colonization of a relatively inert initial substrate. Specifically, the use of sewage sludge for

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Introduction

Quarrying activities produce severe impacts on important ecological functions that provide ecosystem services contributing to human well-being. In most of the scenarios, restoring ecosystem services after finishing the exploitation implies the recovery of vegetation in sites where soil fertility levels have been

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quarry restoration is a management option that contributes to the valorization of mine spoils and sludge from urban wastewater treatment plants (Sopper 1993), in agreement with the EU principles for a more circular economy (Mosquera-Losada et al. 2017). When a Technosol approach is taken, sewage sludge is applied once, at a moderate dosage, to act both as fertilizer and organic amendment, and usually mixed with mining debris before their spreading as a topsoil layer in the restored areas. Sewage sludge is then an interesting option for valorizing mine spoils due to its fertilizing properties (Van-Camp et al. 2004) and its known positive effects on soil aggregate stability (Caravaca et al. 2002; Ojeda et al. 2008), soil water retention (Ojeda et al. 2010, 2011), and vegetation recovery (Moreno-Peñaranda et al. 2004; Ortiz & Alcañiz 2006; Carabassa et al. 2018). However, sewage sludge application also requires strong supervision and monitoring due to certain environmental risks related to its potentially harmful heavy metals and persistent organic pollutant content (Düring & Gäth 2002; Carabassa et al. 2010a).

Pedogenic processes occurring in Technosols are similar to those of natural soils (Leguédois et al. 2016), although the components used can strongly influence their evolution and their capacity to behave as a soil, and therefore, to provide the associated ecosystem services. However, they tend to have a fast evolution compared to natural soils, including biological activity (Leguédois et al. 2016). The last is of importance since soil fauna and vegetation are key factors for the provision of ecosystem services in soils (Tate 2005), but biological activity also drives soil pedogenesis itself, e.g. through its role in carbon and nitrogen dynamics (Frouz et al. 2013).

Soils are responsible for a variety of natural processes known as soil functions that are the basis of the delivery of the so-called ecosystem services (Adhikari & Hartemink 2016). While soil functions refer to the soil benefits for all the ecosystem species, including humans, the term ecosystem service specifically refers to human benefits (Adhikari & Hartemink 2016; Baveye et al. 2016). Because of the difficulties in the direct assessment of ecosystem services, soil functions have been used as indicators of the provision of those services (Baveye et al. 2016). For instance, organic carbon (OC) content has been used as a proxy of carbon sequestration, while the biodiversity of particular groups of organisms has been related to the habitat function of soil. The provision of ecosystem services is the main reason for soil rehabilitation, due to their direct connection with human well-being (UNEP 2008). In the last decade, the ecosystem services concept has been successfully adopted by environmental scientists, media, and governmental agencies, boosted by the publication of the Millennium Ecosystem Assessment (2005). Thus, ecosystem services approaches have been included in a variety of applications, from land planning and the assessment of particular soil management alternatives, to the assessment of restoration success, given the increasing social expectations toward soils in the Anthropocene (Leguédois et al. 2016).

Regarding carbon sequestration in soil, it is generally achieved by any biomass input that originated through a process causing a net removal of atmospheric CO₂-C by plants, and then stored as stable soil organic matter. The storage efficiency of the different pools of organic matter is highly

influenced by its biochemical recalcitrance, its stabilization as organomineral aggregates, the occlusion in soil aggregates, or its transportation into the subsoil (Lal 2003). Sewage sludge, as a biomass derived residue, may directly contribute to soil carbon sequestration through its stabilization in soil, and indirectly through the increase in plant biomass production and litter intake (Ojeda et al. 2015). However, the relatively low stability of sewage sludge (Mattana et al. 2014) is expected to cause transient effects on soil organic matter pools, as mid-term soil organic carbon (SOC) sequestration relies more on the subsequent evolution of OC inputs from plant debris intake to soil rather than on the OC provided by the sludge (Ojeda et al. 2015). Organic matter improvements, in turn, can contribute to other relevant ecosystem services in rehabilitated land such as raw materials production (for fuel, construction materials, etc.), nutrient cycling, climate regulation, or improving soil as habitat for organisms (Baveye et al. 2016). However, little is known about the efficiency of Technosol approaches in terms of soil carbon storage (Ojeda et al. 2015), and especially in the mid and long term, which could be of interest for offsetting the emissions of mining activities closely linked to the cement industry, one of the main contributors to industrial CO₂ emissions (Imbabi et al. 2012).

The use of sewage sludge in Technosols is expected to enhance the biological colonization in the initial stages of the restoration. In previous studies, the use of sewage sludge was shown to strongly influence plant community structure in the short term in a shrubland intended to be converted into a dehesa (Ferreiro-Domínguez et al. 2011; Tarrasón et al. 2014). On the contrary, no significant effects on diversity were found when the reference was the neighboring forest or shrubland (Moreno-Peñaranda et al. 2004). Some negative ecological effects of the use of sewage sludge have been reported elsewhere, such as declines in microbiota, mesofauna, and macrofauna sensitive taxa (Barrera et al. 2001; Giller et al. 2009; Andrés et al. 2011), the promotion of exotic species (Alpert et al. 2000), and decreases in plant biodiversity (Ferreiro-Domínguez et al. 2011). This is of concern given the ecosystem services driven by plants (Lavorel 2013) and soil organisms (Lavelle et al. 2006).

To prevent the negative effects of excessive dosing of sewage sludge that might compromise the provision of ecosystem services of rehabilitated land, some recommendation protocols have been proposed, such as the one used since 2008 in Catalonia by the local environmental authorities (Alcañiz et al. 2009; Carabassa et al. 2010a, 2010b; Department of Territory and Sustainability 2015). This guideline takes into account the mineral substrate characteristics, the stability of the sewage sludge used (recommended to be over 30%), its pollutant burden, the site aptitude (sewage sludge should not be used near wells, water courses, nitrate vulnerable zones, or highly frequented or inhabited areas), among other environmental restrictions. The protocol also states a dosing limit for sludge (50 tonnes/ha) and a maximum increase in labile organic matter in the receiving soils or substrates (0.5%).

The main goal of this article is to assess the mid-term effects (10 years), on two key ecosystem services (carbon sequestration

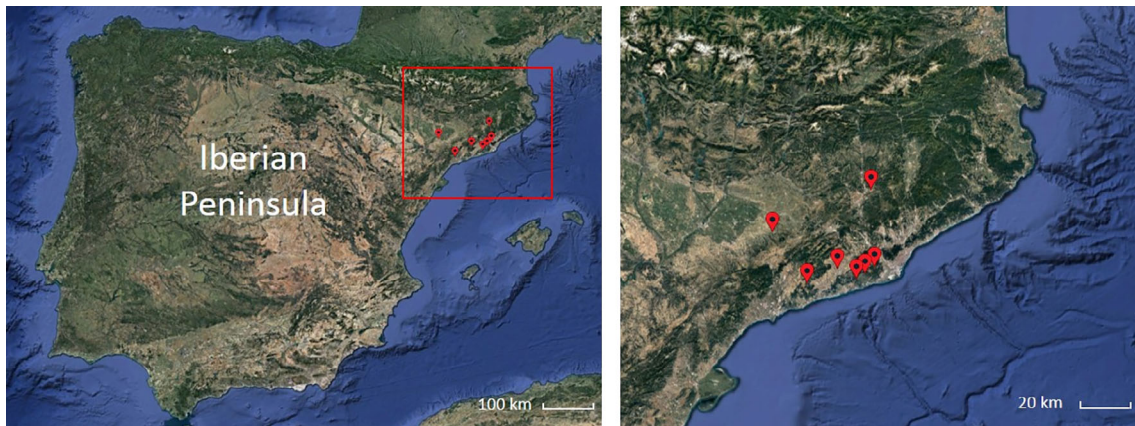


Figure 1. Location of the evaluated quarries on the NE Iberian Peninsula.

and habitat function), of the use of sewage sludge in Technosol construction for limestone quarry restoration, under Mediterranean conditions.

Methods

Study Sites

A set of seven limestone quarry sites, restored 10 years ago using Technosols, were selected, all of them located in the Mediterranean climatic area of Catalonia (NE Iberian Peninsula) (Fig. 1). Each experimental site corresponded to a Technosol constructed using sewage sludge, and a neighboring control area corresponding to a Technosol with the same mineral substrate but without adding sludge (Table 1). Climatic conditions in the different sites mostly differed in terms of water availability, since mean annual precipitation ranged from 400 to 700 mm (from wet to semiarid Mediterranean climate). The reference ecosystem for the restoration was a Mediterranean forest that predominates in the study area, dominated by Aleppo pine (*Pinus halepensis*) usually mixed with holm oak (*Quercus ilex*) and accompanying shrub species (Table 1). Prior to restoration, the areas were used for limestone exploitation for aggregate or concrete production. The evaluated sites (sludge amended and controls) had an average surface area of 3,000 m², and covered many facings, from the most favorable (N face) to the most challenging (S face). The dominant geomorphologic (landform) type is the terrace/berm embankment with steep slopes, some approaching 45°. The subsoil of embankments primarily consisted of fine and/or rocky fractions from extraction debris or excavations, and sometimes with blasting debris.

Technosols Construction

The mineral substrate used for Technosol construction mostly consisted of rocky debris, sometimes mixed with topsoil kept aside from mine topsoiling or excavations. In some cases, the stoniness was very high (over 80%), having a high proportion of carbonates and very low organic matter content (Table 2).

Sewage sludge consisted of an anaerobically digested sludge coming from medium-size municipal wastewater treatment

plants. All of them had enough quality to be used in agriculture, i.e. had relatively high stability (48% as average) and low heavy metal content (Table 3). As usually found in sewage sludge, P concentrations were very high. Sludge was dosed according to its organic matter content, stability degree, and the properties of the mineral substrate (stoniness and bulk density), following Alcañiz et al. (2009) and Carabassa et al. (2010a, 2010b). The average sludge dose used in the different sites was around 45 tonnes/ha (dry weight), and its field application was conducted between autumn 2006 and spring 2007.

Field Sampling and Laboratory Analysis

The parameters assessed in the rehabilitated areas reflect the sludge-based Technosols' ability to improve soil quality, minimize degradation processes, and promote vegetation development. Soil samplings were carried out in 2007 (4–6 months after sludge application) and in May–June 2017 (10–11 years after sludge application). Vegetation measures were carried out in May–June 2017 after 10–11 years of the sludge application. Soil sampling involved taking a composite sample of cores ($n = 12–20$, depth = 0–20 cm) for each restored zone with an Edelman auger.

The soil parameters analyzed were particle size determined by sedimentation—Robinson pipette (Clarke Topp & Ferré 2002), equivalent CaCO₃ by CO₂ volume released after HCl addition—Bernard calcimeter method, electrical conductivity of 1:5 (w:v) water extract, SOC content by acid dichromate oxidation, total nitrogen using the Kjeldahl method, available phosphorous—Olsen, and available potassium (American Society of Agronomy 1982). In each restored area, vegetation measures were taken according to Carabassa et al. (2019): establishing 6 × 10 m transects and measuring the main cover types (herbaceous, shrubs, trees, organic debris, bare soil) by contact-point each 20 cm; shrub and tree density by identifying and counting all the seedlings in 3 × 100-m² plots; flora inventories identifying all the species present; species abundance by qualitative observation of its respective cover.

Table 1. Quarry sites, their location, climatic conditions (precipitation and temperature), slope characteristics (orientation, morphology, steepness, filler material, and lithology), and reference system (plant community of the surrounding area). *Material used to fill the excavation hole for giving the final morphology (geomorphic reclamation) to the restored areas (De la Vergne 2006).

Site	Latitude (N)	Longitude (E)	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)	Orientation	Landform	Maximum Slope (°)	Filler*	Dominant Lithology	Reference System
Aiguamolls	41° 28' 31"	0° 49' 39"	451	14.9	W	Terrace/berm embankment with steep slope	42	Rocky debris	Marl	<i>Thymus vulgaris</i> and <i>Rosmarinus officinalis</i> shrubland with <i>Pinus halepensis</i>
Ponderosa	41° 15' 41"	1° 09' 27"	589	14.9	E	Terrace/berm embankment with steep slope	42	Soil and rocky debris	Limestone	<i>Pinus halepensis</i> forest
Lázaro	41° 12' 07"	1° 28' 57"	505	15.9	SE	Terrace/berm embankment with steep slope	43	Rocky debris	Limestone	<i>Pinus halepensis</i> forest
Fou	41° 21' 32"	1° 54' 34"	684	13.2	NE	Terrace/berm embankment with steep slope	33	Rocky debris	Limestone	<i>Pinus halepensis</i> forest
Vallcarca	41° 15' 13"	1° 52' 25"	535	15.6	NO	Terrace/berm embankment with steep slope	42	Without filler, blasting debris	Marl and limestone	Mixed forest: <i>Quercus ilex</i> and <i>Pinus halepensis</i>
Falconera	41° 15' 40"	1° 53' 12"	545	15.5	NO	Terrace/berm embankment with steep slope	33	Soil and mining wastes	Limestone	<i>Pinus halepensis</i> forest
Montlleó	41° 41' 35"	1° 49' 39"	630	13.7	S	Terrace/berm embankment with steep slope	40	Rocky debris	Marl	<i>Thymus vulgaris</i> and <i>Rosmarinus officinalis</i> shrubland with <i>Pinus halepensis</i>

Table 2. Properties of the soils and mining debris used for the Technosols' construction. *Referring to the fine fraction (<2 mm).

Site	<2 mm (%)	Sand* (%)	Silt* (%)	Clay* (%)	Carbonate* (g/kg)	pH	Organic Matter* (g/kg)	Electrical Conductivity (1:5 extract, dS/m)	Bulk Density (mg/m ³)
Aiguamolls	22	14	50	36	421	8.8	1.0	0.48	1.8
Ponderosa	45	34	33	34	314	8.3	7.0	0.90	1.5
Lázaro	17	50	22	28	734	8.3	2.7	0.27	1.6
Fou	22	21	30	49	426	8.2	7.0	0.58	1.4
Vallcarca	57	46	22	32	271	8.3	3.7	0.37	1.5
Falconera	55	58	21	21	207	8.1	11.9	1.16	1.4
Montlleó	75	41	40	19	390	8.4	8.0	1.96	1.2

Table 3. Physicochemical characterization of the sewage sludge used for Technosol construction. *Percentage of organic matter resistant to acid hydrolysis.

Parameter	Average	Max.	Min.	SD
Dry matter (%)	24.5	26.8	22.5	12.6
Organic matter (%)	57.7	70.7	39.2	27.1
Degree of stability (%)*	48.1	60.1	31.8	17.2
Conductivity (1:5 extract, dS/m 25°C)	2.0	3.0	1.0	0.7
pH (water 1:10 w:v)	7.7	8.5	6.9	0.6
N-Kjeldhal (g/kg)	36.8	63.4	11.5	19.8
N-ammonia (g/kg)	10.7	21.5	1.8	7.3
P-total (g/kg)	38.3	64.4	24.5	23.5
K (g/kg)	2.8	5.7	1.0	1.5
Cu (mg/kg)	322.3	580.0	102.0	170.6
Ni (mg/kg)	23.0	43.3	15.5	13.9
Cr (mg/kg)	56.6	85.6	12.5	35.7
Pb (mg/kg)	54.3	64.2	29.5	28.1
Hg (mg/kg)	2.0	4.2	0.2	1.3
Cd (mg/kg)	3.7	10.0	0.9	3.6
Zn (mg/kg)	1,037.6	2,199.0	375.0	512.6

Data Analysis

Analysis of variance (one-way ANOVA and repeated measures ANOVA) was used to examine differences between treatments (amended and control soils) regarding soil properties (organic matter, N, and P contents), proportion of soil cover in each category (herbaceous, total vegetal, organic debris) and herbaceous development (height), using $p < 0.05$ as the cut-off value for statistical significance throughout the manuscript.

Results

Soil Properties

After 10 years of Technosol construction, sludge-amended soils had significantly higher organic matter, N, and P contents compared to the unamended ones (Fig. 2), achieving a fivefold content increase in one of the sites. Some unamended Technosols were clearly deficient in organic matter, with SOC values below 0.5%. These differences were even stronger in the case of N, where sludge-amended Technosols had more than three times higher contents compared to unamended ones, which were extremely poor in N, especially when only mine spoils were used as mineral substrate. Moreover, P contents showed the

largest contrast between amended and control soils, with very high contents in the sludge-amended Technosols, which were 10 times higher than in unamended soils where values showed a clear deficiency.

Regarding soil C:N ratio (Fig. 3), most soils were well balanced, with a ratio between 8 and 12, which are typical values for A horizons of calcareous Mediterranean forest soils. In general, ratios were similar for amended and unamended soils, except in the Lázaro control treatment, where the C:N ratio was extremely high due its very low N content. Regarding the N:P ratio, controls were deficient in available P and highly unbalanced, mainly when rocky debris without including topsoil were used for Technosol construction.

Comparing the soil property values shortly after Technosol construction (4–6 months) with the results after 10 years (Fig. 4), it was shown that SOC increased in both amended and unamended soils (control areas) but more strongly in the sludge-amended plots, with a 2.1-fold increase compared to the 1.6-fold increase in the unamended Technosols. After 10 years, the control Technosols also failed to achieve the initial SOC levels of sludge-amended ones. Amended soils tended to show significant increases in N and P content after 10 years, but this trend was not observed for P, with nonsignificant changes, despite a tendency to increase (Fig. 5).

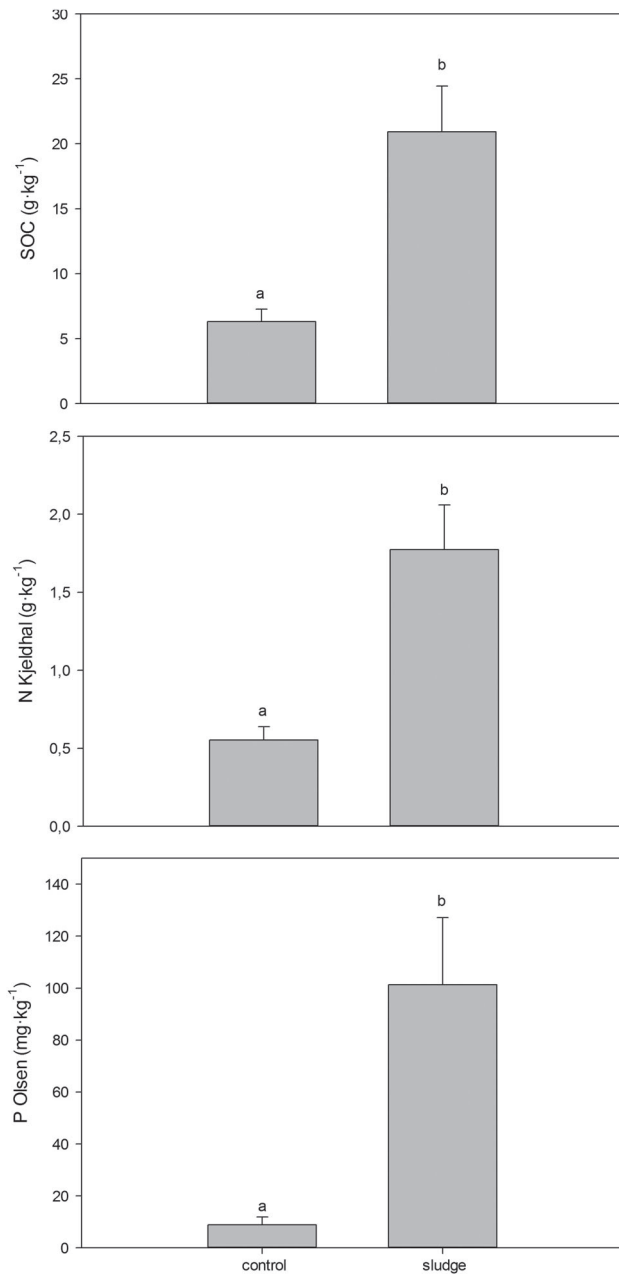


Figure 2. SOC, Kjeldhal N, and Olsen P content in sludge-amended and control Technosols 10 years after their construction. The error bars represent +SE and different letters indicate significant differences at a $p < 0.05$ level.

Considering only the topsoil layer (first 20 cm depth), the average organic C sequestration in sludge-amended Technosols was 28 tonnes C/ha after 10 years, and 9 tonnes C/ha was contained in the unamended ones, which represents a threefold increase in the sequestered C.

Plant Community and Development

After 10 years, herbaceous cover was still dominant in most of the areas evaluated, irrespective of controls or sludge-amended

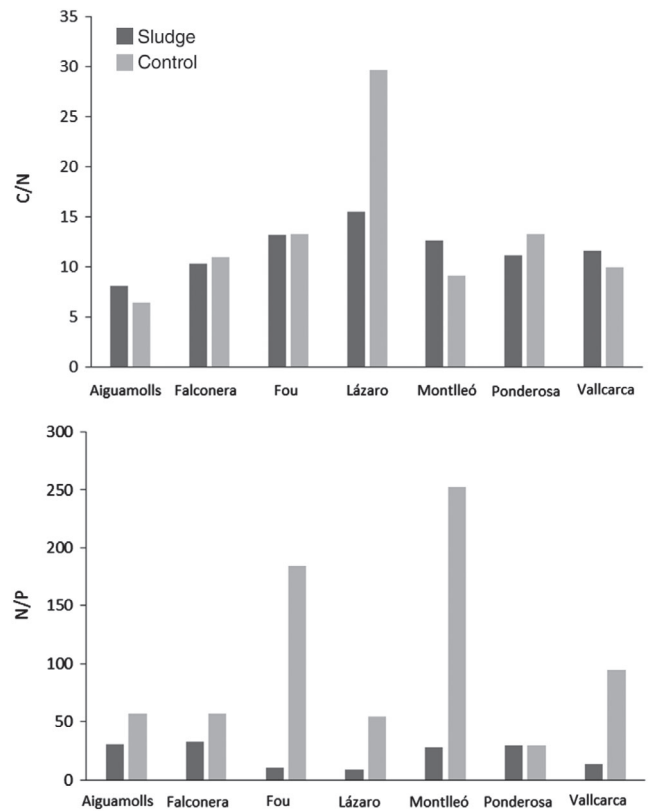


Figure 3. C:N and N:P ratios of sludge-amended and control Technosols 10 years after construction, in the different sites studied.

plots. The average herbaceous cover over all plots was less than 50% (Fig. 6). However, herbaceous vegetation was still more developed in amended plots, where organic debris accumulation was also higher (Fig. 6). Regarding herbaceous species composition, sludge-amended Technosols showed a higher frequency of ruderal species, such as *Chenopodium album*, *Malva sylvestris*, and *Cardus* spp. (Table S1), but they were not dominant. Colonization by native neighboring species was observed in both Technosol approaches. Some silt-tolerant and halophyte plants, like *Salsola kali* or *Atriplex halimus*, were more frequent in sludge-amended soils despite salinity not being significantly higher. Some invasive species such as *Arundo donax* were identified in amended plots, despite the fact that their vegetation cover is minimal, and its presence cannot be attributed to sludge amendment but to its introduction as rhizomes in the exogenous soil used for Technosol construction.

Regarding the shrub and tree strata, sludge-amended plots presented higher woody cover (shrubs and trees), mainly due to enhanced pine growth, which explains the higher total plant cover in this treatment (Fig. 6). The presence of shrubs and trees is mainly explained by plantation actions carried out after Technosol spreading. However, in most areas, recruitment of at least one wild shrub species took place, while this was also true but less usual for tree species. The most common tree species found was Aleppo pine (*Pinus halepensis*), although in some cases holm oak (*Quercus ilex*) was also present at much lower

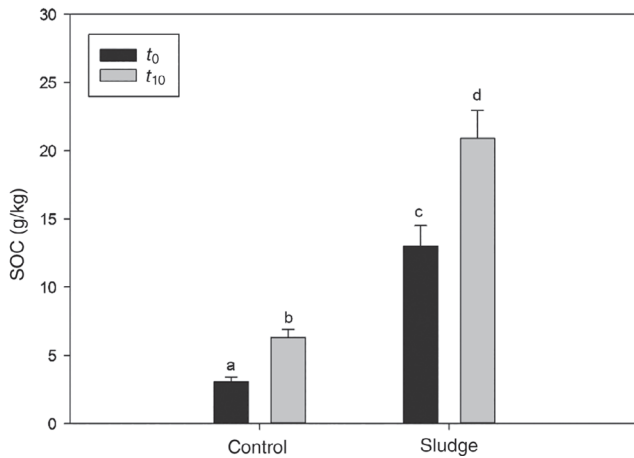


Figure 4. Initial (t_0 , 4–6 months) and 10 years (t_{10}) soil organic carbon (SOC) contents in sludge-amended and control Technosols of studied quarries. The error bars represent +SE and different letters indicate significant differences at a $p < 0.05$ level.

densities (see Table S1). Regarding shrubs, *Dittrichia viscosa*, an extremely common Mediterranean plant of the first stages of secondary succession, had colonized almost all the areas evaluated. Rosemary (*Rosmarinus officinalis*), mastic (*Pistacia lentiscus*), and cotton lavender (*Santolina chamaecyparissus*) were also found in many of the areas evaluated. Most specimens of these bushes were planted, although natural recruitment was also observed, especially in the case of mastic. There were no notable differences between treatments regarding the recruitment of shrub or tree species (see Table S1).

Discussion

After 10 years, Technosols constructed using sewage sludge as an amendment had three times more SOC than the unamended ones. On one hand, it is clear that sewage sludge has contributed to changes in the organic matter content of the soil, but most of its organic matter is labile, which suggests that the direct effects of sludge on soil have only been transient (Tarrasón et al. 2010). On the other hand, plant debris from vegetation grown in restored areas contributes to increased SOC (Muñoz-Rojas et al. 2016) that tends to be stabilized and concentrated in the fine fraction (<2 mm). For this reason, the increase in SOC observed in amended plots after 10 years is more likely due to the contributions of vegetation growth in the area than from the OC directly provided by the sludge. These differences were higher in extremely stony soils (<20% fine fraction) located in moderately rainy regions (700 mm annual precipitation) that allowed herbaceous vegetation to grow after sludge application and rain events. In contrast, fine soils in semi-arid regions (500 mm annual precipitation) did not accumulate such quantities of C in amended soils, due to the smaller positive impact of the amendment on growth of herbaceous vegetation, and consequently differences with respect to control were also lower. This seems to be confirmed by Meersmans et al. (2012), who detected that OC concentrations in fine particle-size fraction

increase with increasing rock fragment content, and that spreading farmyard manure and slurry induces higher carbon concentrations mostly in wet and stony grasslands. Similarly, Arias et al. (2017) found gains of up to 10 tonnes C/ha in the tilled layer (0–30 cm) of stony soils only after 2 years of irrigation.

After 10 years of restoration works, the average SOC of soils amended with sewage sludge was relatively high, while the SOC content in the control areas was very low and clearly deficient (Carabassa et al. 2010a, 2010b; Carabassa et al. 2015). In any case, both amended and unamended soils were still far from the SOC average for Mediterranean forest soils (Lal 2005; Rovira & Ramón Vallejo 2007; Doblás-Miranda et al. 2013), and therefore probably far from any C saturation situation, especially considering the relatively high clay content of soils in this study.

Despite the fact that SOC fractioning was not available in this study, previous studies on Technosols from quarries confirmed that SOC tends to be more stabilized over time in sewage-amended soils, doubling the fraction of nonhydrolyzable carbon in the mid term (Ojeda et al. 2015). Considering that many organic compounds of this nonhydrolyzable fraction are hard to mineralize (Rovira & Ramón Vallejo 2007), we state that this SOC fraction of the sludge-amended mine Technosols could be considered as sequestered carbon. Moreover, in this study all the Technosols had a high carbonate content, which contributes to the formation of aggregates and to the physical protection of SOC (Amézqueta 1999).

Regarding the total amount of carbon sequestered in soils at a world level, the vast majority of the SOC reservoir is reported to be below 20 cm (Fontaine et al. 2007). This deep carbon is highly persistent because it is bonded to soil minerals and it is less accessible for decomposers (Wattel-Koekkoek et al. 2003). However, we only considered the first top 20 cm of soil in our carbon stock estimations. Consequently we underestimated the total SOC, especially on amended plots, due to the strong plant growth in the first years after Technosol construction (Carabassa et al. 2018). This plant growth, which included trees, could have increased deep C through root growth, as shown by Simón et al. (2018) in mine Technosols in SE Spain 6 years after their establishment. Nevertheless, this plausible underestimation might be limited considering the reduced soil depth of the Technosols included in this study.

Regarding nutrient content, some control Technosols were clearly deficient and unbalanced in N and P. This fact might explain the low vegetation success in sites with relatively low hydric stress (700 mm annual precipitation), as N and P are the two main macronutrients limiting plant primary production in terrestrial ecosystems (Elser et al. 2007). This is especially true in Mediterranean forest ecosystems with calcareous soils that reduce P bioavailability (Sardans et al. 2004). Furthermore, nutrient imbalances in the stoichiometric relationship between N and P can have significant impacts on soil functions, affecting the development of vegetation and microbial activity (Sardans et al. 2012).

On the contrary, sludge-amended Technosols still presented high N and P concentrations after 10 years, and in the specific case of N, more than in the short term after sludge

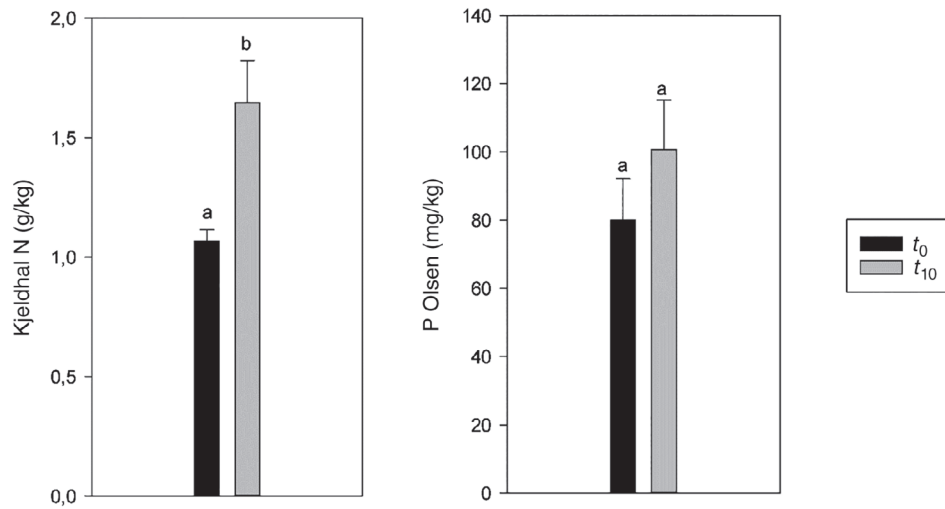


Figure 5. Kjeldhal N and Olsen P contents in sludge-amended Technosols 4–6 months (t_0) and 10 years (t_{10}) after sludge application. The error bars represent +SE and different letters indicate significant differences at a $p < 0.05$ level.

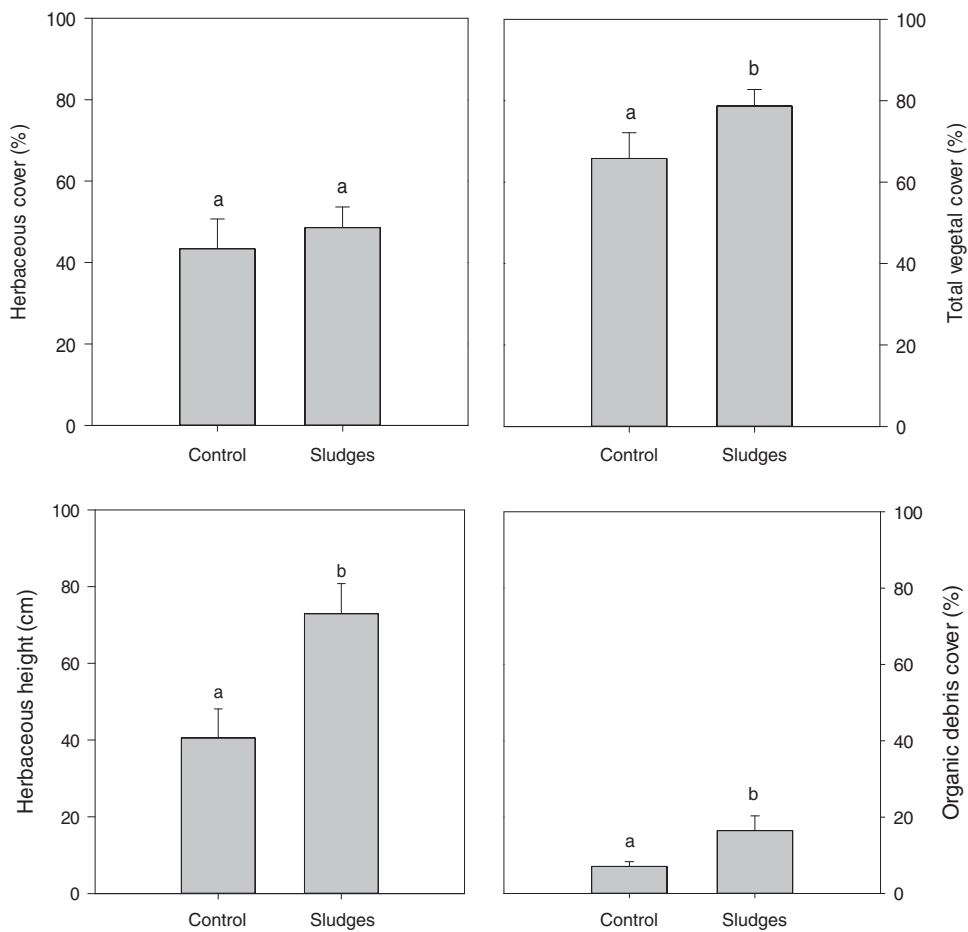


Figure 6. Percentage of plant cover type distribution (herbaceous, total vegetal, organic debris) and herbaceous development (height [cm]) on sludge-amended and control Technosols 10 years after sludge application. The error bars represent +SE and different letters indicate significant differences at a $p < 0.05$ level.

amendment. Although nitrogen leaching is plausible with the sludge treatment, it would mainly take place during the first 4 months due to the high mineralization rates of organic N from sludge (Carabassa et al. 2018). After this period, leaching should decrease quickly due to reduced sludge decomposition rates and the enhanced nitrate absorption by the growing vegetation (Tarrasón et al. 2008; Jordán et al. 2017). As SOC becomes stabilized over time in sludge-amended Technosols (Ojeda et al. 2015), N stabilization in organic forms is also expected, as shown by the balanced C:N ratios observed. Regarding P, and despite its high levels, a low availability is expected due to the alkaline pH of the highly calcareous materials used for Technosol construction that causes a fast immobilization of P as calcium triphosphate (Tunesi et al. 1999).

Regarding total plant cover, significant differences between amended and control Technosols persisted after 10 years. However, despite herbaceous cover being similar in both treatments, herbaceous vegetation was more developed in sludge-amended areas, which was coupled to an enhanced accumulation of organic debris and the consequent higher content of SOC (Wambsganss et al. 2017). Even though the absolute herbaceous cover was less than 50% in both treatments, this was not of concern due to the effective protection against erosion because of the high stoniness of these soils. Moreover, sludge-amended areas had higher cover of woody plants, associated with the high fertilizing effect on pine growth, which in turn also plausibly contributed to the increased SOC. This tree-specific fertilizing effect has been described elsewhere and shown as higher tree growth ratios in soils amended with sludge for restoration purposes (López-Díaz et al. 2009; Tarrasón et al. 2014).

Regarding plant composition, and coupled to the higher N levels, higher relative abundance of nitrophilous species was observed in sludge-amended soils, though those species were not dominant in the community after 10 years. Thus, the species compositions in both types of Technosols were similarly ruderal, in agreement with previous studies conducted 5 years after sludge application (Moreno-Peñaranda et al. 2004). Despite the slowness of this process and the fact that woody species were also present in unamended Technosols (including natural recruitment), enhanced woody (shrubs and trees) species recruitment was observed in sludge-amended plots, which represents an important goal in the restoration of these areas due to the beneficial effect on ecosystem functioning (Soliveres et al. 2014). This shows that Technosols constructed with mine spoils without organic amendment are less successful in terms of vegetation development and community complexity, mostly due to the extremely low fertility of the quarry substrates.

In summary, after a decade, Technosols constructed with moderate dosages of sewage sludge boosted soil organic matter enrichment and carbon sequestration, as they contained three times more SOC than the unamended ones. This was the result of increased primary production due to the high nutrient content of sludge, which was still visible after 10 years. Plant cover was also enhanced in Technosols receiving sludge, without causing strong changes in plant community but demonstrating higher development of shrubs and trees that might reflect a speed up in the natural succession process. All of these benefits are clearly

linked to the two main soil ecosystem services that are intended to recover in the restoration of quarrying activities, which are biological habitat and carbon sequestration. Furthermore, we demonstrate that the valorization of “in situ” mine spoils can be successful and improved by the use of sewage sludge, in agreement with the current principles of the circular economy.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. List of species identified in the areas evaluated and relative abundance depending on the contribution to the vegetal cover.

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