Sewage sludge as an organic amendment for quarry restoration: Effects on soil and vegetation

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Abstract
Quarry restoration in Mediterranean environments usually needs organic amendments to improve the substrates used for technosol construction. Digested sewage sludges from municipal wastewater treatment plants are rich in organic matter, N, and P and constitute an available and economically interesting alternative for substrate amendment. However, their pollutant burden and labile organic matter content involve an environmental risk that must be controlled. Moreover, ecological succession in restored areas can be influenced by the use of sludge and should be assessed. To minimize these risks, a new sewage sludge dose criterion relating to its labile organic matter and heavy metal content has been established. Sewage sludge doses currently range between 10 and 50 Mg ha\(^{-1}\). In order to verify the suitability of this dose criterion, 16 areas rehabilitated using sewage sludge located in limestone quarries in a Mediterranean climate in Catalonia (NE Spain) have been assessed. These evaluations focused on physicochemical properties of rehabilitated soils, land degradation processes, and ecological succession. In the short term, 6 months after sludge application, an increment of organic matter content in the restored soils was observed, without significant increases in electrical conductivity or heavy metals content, and with a dense plant cover that contributes to effective soil erosion control. Two years after, ruderal plants were still present but later successional species colonized the restored zones in different degrees. These results suggest that sewage sludge, used as a soil amendment according to the proposed methodology, can safely improve technosol quality without constraints that compromise ecological succession.

KEYWORDS
erosion control, organic amendment, quarry restoration, soil rehabilitation, stability degree, technosol

1 INTRODUCTION

Restoration ecologists have long recognized the role of soil, particularly its physical and chemical properties, in the successful revegetation of degraded sites (Heneghan et al., 2008; Jordan, Giplin, & Aber, 1987). Starting from this premise, ecological restoration principles applied to quarry restoration imply in many cases the use of their own mine spoils (Jordán, Pina, García-Orenes, Almendro-Candel, & García-Sánchez, 2008; Ram et al., 2006; Tedesco, Teixeira, Medina, & Bugin, 1999), mainly when topsoil stripping is not possible or does not give a sufficient quantity of soil. However, these materials usually do not meet the minimum fertility requirements for their direct use as soil substitutes in land restoration and have to be improved using organic amendments. In this context, the use of sewage sludge as organic amendment could represent an economically and environmentally effective alternative to create a new fertile substrate, currently named technosol, for plant growth. Sewage sludge contains nutrients and trace elements essential for plant growth (Ortiz & Alcañiz,
and organic matter, which can act as a soil conditioner to improve the physical properties, such as soil aeration and water-holding capacity (Singh & Agrawal, 2008; Sort & Alcaníz, 1999). However, their pollutant burden, comprising heavy metals and a variety of organic compounds, needs to be controlled. In this sense, there are some legislative regulations (European Union, 1986) and proposals (European Union, 2000) that establish maximum levels of heavy metals and organic pollutants in sewage sludge and receiving agricultural soils.

Organic amendments with high labile organic matter content are not suitable for land rehabilitation as this type of organic matter can be quickly mineralized, releasing large amounts of nutrients, which limits its positive effects to a short time. Moreover, in studies carried out with different types of organic wastes, a negative correlation between the degree of stability of organic matter (the proportion of stable, not labile, organic matter) and toxicity to plants and/or soil fauna has been described (Domene, Alcaníz, & Andres, 2007; Fuentes et al., 2004; Ramírez, Domene, Ortiz, & Alcañiz, 2008). Furthermore, a strong correlation between the stability degree and total nitrogen, hydrolysable nitrogen, and NH₄-N content has been found (Ramírez et al., 2008). At the field level, high amounts of available nitrogen in rehabilitated soils promote ruderal plant species predominance (Moreno-Peñaranda, Lloret, & Alcañiz, 2004), which makes ecological succession difficult, and poses a risk for groundwater contamination (Navarro-Pedreno, Almendro Candel, Jordán Vidal, Mataix-Solera, & García-Sánchez, 2004). Regarding groundwater pollution by heavy metals, these do not pose a real risk because heavy metals mobility in water is very low (Hornburg & Brummer, 1993).

In order to limit or avoid these unintended situations, a new dose calculation protocol for organic amendments to be used as soil amendments has been proposed (Alcañiz, Ortiz, & Carabassa, 2009; Carabassa, Serra, Ortiz, & Alcañiz, 2010). Relating to organic amendment characteristics, only stabilized amendments are allowed, with a recommendation for stable organic matter content greater than 30% (i.e., amendments containing a maximum amount of labile organic matter of 70%). In order to prevent heavy metal pollution, the protocol recommends avoiding sewage sludge and soils with metal concentrations above the limits proposed by the European Union (2000), and do not reach these limits on the resulting technosols. Moreover, in soils or substrates having more than 20 g kg⁻¹ of organic matter, sewage sludge amendment is not recommended.

On the other hand, alongside this dose calculation protocol, a site-aptitude evaluation methodology has been designed with the objective of avoiding applications on unsuitable areas such as sites vulnerable to pollution and protected groundwater recharge areas. The items (topics) included in this evaluation procedure are the proximity of the zone to be restored to wells or watercourses, the location of a quarry in a zone with aquifers vulnerable to nitrate contamination, the water table depth, the accessibility and the space for storage and mixing of sludge with soil, site visitation frequency, farming utilization, and the proximity to inhabited sites. Additionally, if the evaluation procedure determines that a site is suitable for sewage sludge use, a maximum area of 2 ha per year may be restored using this amendment. This protocol is currently being used by the Waste Agency of Catalonia (NE Spain) and by waste management companies to calculate sludge doses and sludge application conditions for their use in quarry restoration works (Department of Territory and Sustainability, 2015).

The main goal of this paper is to introduce the dose criteria proposed and to evaluate the effects of sewage sludge application as a technosol amendment from an ecological restoration point of view. To do this, soil quality parameters, degradation processes, and plant composition, as indicators of ecological succession, have been evaluated.

2 | METHODS

2.1 | Sludge-dose criteria

According to the protocol described in Alcañiz et al. (2009) and Carabassa et al. (2010), sewage sludge is dosed depending on its organic matter stability, determined by weight loss-on-ignition at 550°C after acid hydrolysis. The protocol proposes 5 g kg⁻¹ as a maximum amount of labile organic matter added by the sludge on the amended soil. Other parameters such as the organic matter content of the sludge, the thickness of the technosol layer to be applied (0.4 m maximum), the bulk density, and the percentage of the <2 mm size fraction are considered in the dose-calculation formula:

\[
D_{\text{DM}} = T \cdot B_{\text{DE}} \cdot F_E \left(5 \cdot \frac{S}{1 - S}\right) \cdot \frac{1}{\text{OM}_5} \cdot 10,
\]

where \(D_{\text{DM}}\) is the dose of sludge (Mg ha⁻¹, dry weight); \(T\) is the desired thickness of the substrate layer to be applied (m); \(B_{\text{DE}}\) is the bulk density of the mineral substrate (Mg m⁻³); \(F_E\) is the proportion of <2 mm size particles of the mineral substrate (g kg⁻¹); \(S\) is the degree of stability of the sludge (g kg⁻¹); and \(\text{OM}_5\) is the proportion of organic matter in the sludge (g kg⁻¹).

Moreover, as a preventative measure, this protocol fixes a maximum dose of sludge (50 Mg ha⁻¹, dry weight), based on earlier experience obtained from ecotoxicological assays using plants and soil fauna (Domene et al., 2007; Tarrásón, Ojeda, Ortiz, & Alcañiz, 2008).

2.2 | Restored zones selected

A set of 16 areas located in 11 quarries that were restored using their respective mine spoils and amended with sewage sludge according to the current protocol were selected (Table 1). These quarries are located in Mediterranean environments encompassing a climatic gradient from semiarid to subhumid. Mining activities exploiting diverse calcareous materials that could influence the restoration processes were included. Mine spoils were the main substrate used to create a technosol for topsoil rehabilitation. All the substrates were calcareous (30% to 70% of carbonate content) and stony, but with more than 30% of <2 mm particle-size fraction and a loamy texture.

The average sewage sludge dose was 40 ± 13 Mg ha⁻¹ (mean ± SD, dry weight basis). All sludge applied came from municipal wastewater treatment plants close to the mining areas, having been subjected to an anaerobic digestion process and partially dehydrated (Table 2). The organic matter content of these sludges and their stability degree was relatively high. They had high concentrations of nitrogen and phosphorous, similar to those currently applied to agricultural soils.
The heavy metal content was low and always met the requirements of the European Union (2000).

Steep slopes (60–75%) are the predominant restored surfaces in the mine sites selected, with some exceeding 100%. On these slopes, a layer of about 20 cm of amended substrates (mainly mine spoils mixed with sewage sludge) was spread on top. The average area of restored slopes per site is 4,500 m².

2.3 Evaluation parameters

The parameters evaluated in the restored zones are related to soil quality, degradation processes, and vegetation. Soil samples were taken 4–6 months after sludge application, but degradation processes and vegetation data were assessed after 24 months. Soil sampling involved taking a composite sample of cores (n = 12–20, d = 0–20 cm) for each restored zone. The analysed parameters in soil samples were as follows: particle size determined by sedimentation-Robinson pipette (Gee & Or, 2002), equivalent CaCO₃ by CO₂ volume released after HCl addition-Bernard calcimeter method (Nelson, 1982), electrical conductivity of 1:5 water extract (Rhoades, 1982), organic carbon content by acid dichromate oxidation (Nelson & Sommers, 1982), total nitrogen using the Kjeldahl method (Bremner & Mulvaney, 1982), available phosphorus-Olsen phosphorus (Olsen & Sommers, 1982), and potassium (Knudsen, Peterson, & Pratt, 1982), and heavy metals by mass spectrometry analysis (Thomas, 2004). Geotechnical and soil degradation processes were estimated through direct measures and observations in the field, and erosion losses were estimated by measuring the rill volume. Vegetation measures were taken by establishing transects and sampling plots (10-m transects, 100-m² plots, 3 per area).

3 RESULTS AND DISCUSSION

Soil quality indicators of technosols were evaluated after one growing season (spring or autumn; Table 3). The electrical conductivity of amended soils remained low, with the only exception of two cases that were greater than 2 dS m⁻¹, and organic carbon contents were almost always higher than 10 g kg⁻¹, and with an average increment of 11.2 ± 7.8 g kg⁻¹ (mean ± SD) caused by the addition of the sludge to the mineral substrate that constitutes the mineral fraction of the technosol. Phosphorus content tended to be high and correlated to the mineral substrate that constitutes the mineral fraction of the technosol. Phosphorous content tended to be high and correlated to the organic matter content, having a C/N ratio close to 10, and relating to the sludge dose applied. Available potassium content tended to be low, especially in very rich calcium soils. Heavy metal content was low in the amended soils. Minor increases in the concentrations of these elements were observed after the addition of sewage sludge, all below the European upper limits for agricultural soils (Table 4).

Soil quality parameters indicate that sewage sludge application causes a substantial improvement of organic matter and nutrient content in the amended technosols, as reported in other works (Albiach, Canet, Pomares, & Ingelmo, 2001; Heras, Manas, & Labrador, 2005). Despite the noticeable increase in the soil nutrients due to sludge
to the high mineralization rates of organic matter, which could then leach from the soil and contaminate aquifers. However, nitrogen leaching, if it occurs, should be taken into account that this risk is relatively low due to the small surface restored (<2 ha in a quarry per year) and because sludge is applied only once, compared to agricultural applications where sludge is applied recurrently at the same plot. On the other hand, a fraction of the growing plants, reducing the risk of aquifer eutrophication. Moreover, the metal bioavailability in the studied technosols is expected to be low, according its pH and lime content (Ortiz & Alcañiz, 2006).

No noticeable water erosion or other soil degradation processes were observed 24 months after sludge application. Only in two cases, stability issues (landslides and fallen rocks) were reported due to the excessive slope (greater than 100% in some sites). Rill erosion was detected in seven restored zones although the estimated erosion rates were always below 6 Mg ha\(^{-1}\) yr\(^{-1}\), which can be considered an acceptable rate in slopes and surfaces of recently restored areas (Verheijen, Jones, Rickson, & Smith, 2009), with the one exception of Las Cuevas quarry, where the Z1 zone was severely affected (Table 5).

Dense plant cover was observed in the evaluated zones 2 years after sludge application. The average plant cover was 70 ± 24% and herbaceous plant height 0.45 ± 0.30 m. Concerning species richness, more than 20 plant species were identified in the evaluated zones. Regarding herbaceous vegetation (see Figure 1), grasses were the most frequent functional group of plants (p < 0.015). However, some reported herbaceous species can be considered as ruderal plants that grow in nutrient-rich and disturbed habitats, usually resulting from human activity. Legumes are also well represented in sewage sludge revegetated zones at a similar frequency to Asteraceae and ruderals. No exotic or invasive species were observed in the evaluated zones, despite the presence of some individuals of Arundo donax in one zone (Falconera Quarry) before sludge application.

The observation of vegetation succession showed that native species started to colonize the amended zones 2 years after sludge amendment. Herbaceous species were the main colonizers, being found in half of the amended zones. Shrub species appeared in four restored zones, especially Santolina chamaecyparissus and Rosmarinus officinalis. Moreover, in approximately 60% of the rehabilitated zones where shrubs were planted, spontaneous reproduction of these species was observed.

Vegetation cover is a key parameter for soil stabilization and erosion control (Bochet, García-Fayos, & Tormo, 2010; Espigares, et al., 2020).

### TABLE 3: Summary of physical and chemical parameters of amended substrates (technosols)

| Parameter                          | Average | Max. | Min. | SD |
|-----------------------------------|---------|------|------|----|
| Fraction >5 cm (% ws)             | 3       | 10   | 0    | 3.5 |
| Fraction 5–1 cm (% ws)            | 23      | 40   | 8    | 9.1 |
| Fraction 1–0.2 cm (% ws)          | 21      | 42   | 8    | 8.1 |
| Fine earth <0.2 cm (% ws)         | 53      | 87   | 31   | 15.7|
| Sand (%)                          | 35      | 60   | 16   | 12.9|
| Silt (%)                          | 41      | 63   | 25   | 11.3|
| Clay (%)                          | 23      | 28   | 14   | 4.4 |
| CaCO\(_3\) eq. (%)                | 52      | 80   | 29   | 14.7|
| pH water (1:2.5 w:v)              | 8.1     | 8.5  | 7.9  | 0.2 |
| Electrical conductivity           | 1.02    | 2.94 | 0.3  | 0.8 |
| Organic carbon (g kg\(^{-1}\))    | 11.3    | 23.4 | 2.1  | 4.1 |
| N-Kjeldhal (g kg\(^{-1}\))        | 1.1     | 1.9  | 4.0  | 3.0 |
| P-Olsen (mg kg\(^{-1}\))          | 66      | 103  | 13   | 25.4|
| K-available (mg kg\(^{-1}\))      | 116     | 244  | 76   | 41.0|

Note. N = 28. Data relate to the fine fraction (<2 mm), except coarse particle size fractions that are reported as percent of whole soil sample (ws).

mineralisation, electrical conductivity did not rise greatly. Available phosphorous levels were increased by sludge addition but were in a high-medium range compared with agricultural soils of the region (Peñuelas, Sardans, Alcañiz, & Poch, 2009). However, partial immobilization could take place due to the alkaline pH of these highly calcareous soils. According to sludge composition, mineral nitrogen levels may rise just after sludge application, particularly in ammonium form (not measured in our soil samples). This ammonium nitrogen may rapidly turn into nitrates in these calcareous soils (Kleber, Nikolaus, Kuzyakov, & Stahr, 2000), which could then leach from the soil and contaminate aquifers. However, nitrogen leaching, if it occurs, should take place mainly in the first 4 months after sludge application due to the high mineralization rates of organic-N from sludge. After this, leaching risk should decrease quickly due to nitrate absorption by the roots of the growing plants, reducing the risk of aquifer eutrophication (Jordán et al., 2017; Tarrasón et al., 2008). Moreover, the metal bioavailability in the studied technosols is expected to be low, according its pH and lime content (Ortiz & Alcañiz, 2006).

### TABLE 4: Heavy metal concentration on amended soils and average and maximum increments relating to original mine spoils

| Zone code | Cd   | Cu   | Cr   | Hg   | Ni   | Pb   | Zn   |
|-----------|------|------|------|------|------|------|------|
| Average   | 0.100| 20.8 | 25.1 | 0.062| 19.1 | 27.2 | 77.5 |
| Max.      | 0.500| 50.0 | 40.0 | 0.097| 29.0 | 55.0 | 190.0|
| Min.      | 0.100| 6.0  | 7.0  | 0.041| 11.0 | 11.0 | 18.0 |
| SD        | 0.005| 10.7 | 9.4  | 0.024| 5.7  | 14.9 | 39.9 |
| Limits proposed by European Union (2000) for alkaline soils | 1.5 | 100 | 100 | 1 | 70 | 100 | 200 |
| Average increase | nd | 0.3 | 1.8 | nd | 2.1 | 2.1 | 4.4 |
| Maximum increase | nd | 2.1 | 11.5 | nd | 12.0 | 11.5 | 14.5 |

Note. Z1, Z2, and Z3 refer to diverse slopes or zones in the same quarry. N = 28. nd: no detected; units: mg kg\(^{-1}\).
TABLE 5 Surface of soil affected by water erosion, erosion rates, and soil loss on the evaluated zones of quarries where soil erosion has been detected

| Zone code     | Affected area (m²) | Erosion rate (Mg ha⁻¹ yr⁻¹) | Soil loss (Mg ha⁻¹) |
|---------------|--------------------|------------------------------|---------------------|
| Aiguamolls Z1  | 1,225              | 2.3                          | 5.3                 |
| Aiguamolls Z2  | 1,870              | 0.3                          | 0.7                 |
| Aiguamolls Z3  | 1,950              | 2.2                          | 5.0                 |
| Lázaro        | 1,800              | 0.4                          | 0.9                 |
| Cubetas       | 8,040              | 1.9                          | 4.5                 |
| Cuevas Z1     | 2,000              | 17.3                         | 55.4                |
| Cuevas Z2     | 4,400              | 3.2                          | 10.0                |

Note. Z1, Z2, and Z3 refer to diverse slopes or zones in the same quarry.

FIGURE 1 Frequency of different herbaceous plant functional groups in the evaluated zones of quarries. The error bars indicate standard error (p < 0.02) [Colour figure can be viewed at wileyonlinelibrary.com]

Moreno-de las Heras, & Nicolau, 2011; Merlin, di Gioia, & Goddon, 1999), mainly in major civil works such as the construction of motorways, the rehabilitation of quarries or dumps, and even the creation of ski slopes. Several authors (Albiach et al., 2001; Pond, White, Milczarek, & Thompson, 2005) have demonstrated that soils amended with sewage sludge favour a fast vegetal recovery and plant growth, especially for herbaceous vegetation, which is the best way to control soil erosion in steep slopes. Moreover, sewage sludge promotes soil aggregation (Ojeda, Alcañiz, & le Bissonnais, 2008; Sort & Alcañiz, 1996; Sort & Alcañiz, 1999), reducing soil erodibility. These combined beneficial effects of sewage sludge on vegetation development and soil structure are probably the main reasons explaining the reduced erosion rates found on steep slopes that are especially vulnerable to soil erosion, in the studied quarries.

The relatively lower frequency of ruderal species found in this work (see Figure 1) compared with a previous study of the same team (Moreno-Peñaranda et al., 2004) that showed a dominance of ruderal plants on sewage sludge amended zones must be discussed. This apparent discrepancy may be explained by the different doses of sludge applied, which were lower in the present work (calculated following the protocol reported in Carabassa et al., 2010) compared to other previous studies (Alcañiz, Comellas, & Pujolà, 1996; Barnhisel, Darmody, & Daniels, 2000; Jordà & Andrés, 2000; Moreno-Peñaranda et al., 2004; Morera, Echeverría, & Garrido, 2002; Sopper, 1993).

Therefore, the main difference is the quantity and quality of the organic matter added to the mineral substrate. As explained in the methods section, the new procedure calculates the dose of sludge according to its concentration of stable organic matter (stability degree) and fixes the maximum dose at 50 Mg ha⁻¹. These criteria imply an addition of a limited proportion of labile organic matter and a relatively low addition of total organic matter associated with sludge application, which contributes to reduce the development of ruderal plants currently associated with overfertilized soils. However, the presence of ruderal plants in restored areas may be common also when organic amendments are not used (Alpert, Bone, & Holzapfet, 2000; Hobbs & Atkins, 1988; Moreno-Peñaranda et al., 2004). Therefore, the use of sewage sludge in appropriate doses should not be considered as a barrier regarding plant community succession towards the natural surrounding vegetation. Furthermore, the noticeable recruitment of native shrub species may suggest a plant community convergence with adjacent undisturbed habitats in the medium term. However, this process should be monitored in the long term, as it is one of the main objectives of ecological restoration (Society for Ecological Restoration International Science & Policy Working Group, 2004). Moreover, an increasing emphasis will be focused on the proper ecological functionality of a restored site, and to a lesser extent on returning a restored site back to previous conditions based on species composition (Harris, Hobbs, Higgs, & Aronson, 2006).

4 | CONCLUSIONS

For the range of climatic and soil conditions tested in this work, the use of sewage sludge for vegetation recovery purposes in restoration works is a good alternative that allows the valorization of sewage sludge and increases the quality and stability of restored areas, reducing the risk of soil erosion. One of the most important parameters to take into account for sewage sludge dosage is the amount of labile organic matter, in order to avoid compromising encroachment and reduce the risk of nitrate contamination. Moreover, an aptitude evaluation of sludge, mineral substrates, and location is mandatory before sludge application in order to prevent contamination and detrimental impacts on inhabited zones.

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