This is the **submitted version** of the article:

Carabassa, Vicenç; Ortiz Perpiñà, Oriol; Alcañiz, Josep M. Sewage sludge as an organic amendment for quarry restoration : effects on soil and vegetation. DOI 10.1002/ldr.3071

LDD Land Degradation & Development

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

Journal:	*Land Degradation & Development*
Manuscript ID	LDD-17-0356.R3
Wiley - Manuscript type:	Short Report
Date Submitted by the Author:	04-Jun-2018
Complete List of Authors:	Carabassa, Vicenç; CREAF, CREAF Alcañiz, Josep M.; Universitat Autonoma de Barcelona Centre de Recerca Ecologica i Aplicacions Forestals, CREAF; Universitat Autonoma de Barcelona, BABVE Ortiz-Perpiñá, Oriol; Universidad de Zaragoza Escuela Politecnica Superior de Huesca, Ciencias Agrarias y del Medio Natural
Keywords:	organic amendment, stability degree, erosion control, soil rehabilitation, quarry restoration

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

Authors and addresses: Vicenç Carabassa[1*], Oriol Ortiz[1,2], Josep M. Alcañiz[1,3]

[1]CREAF, Cerdanyola del Vallès 08193, Spain

[2]Escuela Politécnica Superior, University of Zaragoza, Carretera Cuarte s/n, E-22071 Huesca, Spain

[3]Universitat Autònoma de Barcelona, Departament de Biologia Animal, Biologia Vegetal y Ecologia, Cerdanyola del Vallès 08193, Spain

[*] Address correspondence to V. Carabassa, phone: 0034 93 581 3355, e-mail: v.carabassa@creaf.uab.es

ABSTRACT

Quarry restoration in Mediterranean environments usually needs organic amendments to improve the substrates used for technosol construction. Digested sewage sludge from municipal wastewater treatment plants are rich in organic matter, N and P and constitute an available an 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 criteria 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, sixteen 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, six 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: soil rehabilitation, organic amendment, stability degree, Technosol, erosion control, quarry restoration

INTRODUCTION

Restoration ecologists have long recognized the role of soil, particularly its physical and chemical properties, in the successful revegetation of degraded sites (Jordan et al., 1987; Heneghan et al., 2008). Starting from this premise, ecological restoration principles applied to quarry restoration implies in many cases the use of their own mine spoils (Tedesco et al., 1999; Ram et al., 2006; Jordán et al., 2008), 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, 2006), and organic matter, which can act as a soil conditioner to improve the physical properties, such as soil aeration and water-holding capacity (Sort & Alcañiz, 1999; Singh & Agrawal, 2008). 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 mineralised, 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 (Fuentes et al., 2004; Domene et al., 2007; Ramírez et al., 2008). Furthermore, a strong correlation between the stability degree and total nitrogen, hydrolysable nitrogen and NH_4-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 et al., 2004), which makes ecological succession difficult, and poses a risk for groundwater contamination (Navarro-Pedreno et al., 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, 1994).

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 et al., 2009; Carabassa et al., 2010). Relating to organic amendment characteristics, only stabilised 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 draft of the European Commission (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, protected groundwater recharge areas, etc. 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 (DTS, 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.

METHODS

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 (LOI) 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:

$$D_{DM} = T \cdot BD_E \cdot FE \cdot \left(5 + \frac{5 \cdot S}{1 - S}\right) \cdot \frac{1}{OM_S} \cdot 10$$

Where D_{DM} is the dose of sludge (Mg ha^{-1}, dry weight); T is the desired thickness of the substrate layer to be applied (m); BD_E is the bulk density of the mineral substrate (Mg m^{-3}); FE 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 OM_S 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, Tarrasón et al., 2008).

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 sub-humid. 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 metals 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 m^2.

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: particle size determined by sedimentation-Robinson pipette (Gee & Or, 2002), equivalent $CaCO_3$ by CO_2 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 phosphorous-Olsen phosphorous (Olsen & Sommers, 1982) and potassium (Knudsen et al., 1982), and heavy metals by ICP-MS 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 (10m transects, 100m^2 plots, 3 per area).

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}. Organic C contents were almost always higher than 10 g kg^{-1}, 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. Phosphorous content tended to be high and correlated with the amount of sewage sludge added. Total nitrogen concentrations were balanced 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 metals 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 et al., 2001; Heras et al., 2005). Despite the noticeable increase in the soil nutrients due to sludge 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 et al., 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 et al., 2000), which could then leach from the soil and contaminate aquifers. However, nitrogen leaching, if it occurs, should take place mainly in the first four 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 roots of the growing plants, reducing the risk of aquifer eutrophication (Tarrassón et al., 2008; Jordán et al., 2017). Moreover, it has to 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 organic matter from sewage sludge persists in soil due to its recalcitrant composition (e.g. some lipids and aromatic hydrocarbons), and a labile organic matter fraction could also remain in soil protected as aggregates or by sorption on mineral surfaces (Ojeda et al., 2015).

The total amount of heavy metals in the amended technosols never exceeded the concentrations fixed by the European Union proposal (2000), which is stricter than the current European Directive that regulates the agricultural use of sewage sludge. This is due to the relatively low concentration of these elements in the sewage sludge but also to the moderate doses applied. 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} y^{-1}, which can be considered an acceptable rate in slopes and surfaces of recently restored areas (Verheijen et al., 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 two 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 two 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 (Merlin et al., 1999; Bochet et al., 2010; Espigares et al., 2011), 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 et al., 2005) have demonstrated that soils amended with sewage sludge favor 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 (Sort & Alcañiz, 1996; Sort & Alcañiz, 1999; Ojeda et al., 2008), 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 (Sopper, 1993; Alcañiz et al., 1996; Barnhisel et al., 2000; Jorba & Andrés, 2000; Morera et al., 2002; Moreno-Peñaranda et al., 2004). 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 contribute to reduce the development of ruderal plants currently associated with over-fertilized soils. However, the presence of ruderal plants in restored areas may be common also when organic amendments are not used (Hobbs & Adkins, 1988; Alpert et al., 2000; 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 (SER, 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 et al., 2006).

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.

ACKNOWLEDGEMENT

The work described in this paper was funded by the Department of Territory and Sustainability of the Government of Catalonia (Spain).

LITERATURE CITED

Albiach, R., R. Canet, F. Pomares and F. Ingelmo. 2001. Organic matter components and aggregate stability after the application different amendments to a horticultural soil. *Bioresource Technology* **76**:125–129. DOI: 10.1016/S0960-8524(00)00166-8

Alcañiz, J. M., L. Comellas and M. Pujolà. 1996. Manual de restauració d'activitats extractives amb fangs de depuradora. Barcelona: Junta de Sanejament, Generalitat de Catalunya.

Alcañiz, J.M., O. Ortiz and V. Carabassa. 2009. Utilización de lodos de depuradora en restauración. Manual de aplicación en actividades extractivas y terrenos marginales. Barcelona: Agència Catalana de l'Aigua, Generalitat de Catalunya.

Alpert, P., E. Bone, and C. Holzapfet. 2000. Invasiveness, invasibility and the role of environmental stress in the spread of non-native plants. *Perspectives in Plant Ecology, Evolution and Systematics* **3**:52-66. DOI: 10.1078/1433-8319-00004

Barnhisel, R. I., R. G. Darmody and W.L. Daniels. 2000. Reclamation of drastically disturbed lands. Agronomy series n.º 41. Madison: Am. Soc. Agronomy, SSSA.

Bochet, E., P. García-Fayos and J. Tormo. 2010. Can we control erosion of roadslopes in semiarid mediterranean areas? Soil improvement and native plant establishment. *Land Degradation and Development* **21**:110-121. DOI: 10.1002/ldr.911

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-total. In: Page, A.L. (Ed.), Methods of soil analysis. Part 2, second ed., Agron. Monogr., 9. Madison: American Society of Agronomy and Soil Science Society of America.

Carabassa V., E. Serra, O. Ortiz and J.M. Alcañiz. 2010. Sewage Sludge Application Protocol for Quarry Restoration (Catalonia). *Ecological Restoration* **28**:420-422. DOI: 10.1353/ecr.2010.0047

Domene, X., J.M. Alcaniz and P. Andres. 2007. Ecotoxicological assessment of organic wastes using the soil collembolan Folsomia candida. *Applied Soil Ecology* **35** (3), 461–472. DOI: 10.1016/j.apsoil.2006.10.004

Department of Territory and Sustainability, 2015. RESTOFANGS. La restauració superficial edàfica amb fangs de depuradora (available in http://mediambient.gencat.cat/ca/05_ambits_dactuacio/empresa_i_produccio_sostenible/restauracio_dactivitats_extractives/productes-emprats-a-la-restauracio-ambiental/restofangs/index.html)

Espigares, T., M. Moreno-de las Heras and J.M. Nicolau. 2011. Performance of Vegetation in Reclaimed Slopes Affected by Soil Erosion. *Restoration Ecology* **19**:35-44

European Union. 1986. COUNCIL DIRECTIVE of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC) (available in http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31986L0278)

European Union. 2000. Working document on sludge (3rd draft) (available in http://ec.europa.eu)

Fuentes, A., M. Llorens, J. Saez, M.I. Aguilar, J.F. Ortuno and V.F. Meseguer. 2004. Phytotoxicity and heavy metals speciation of stabilised sewage sludges. *Journal of Hazardous Materials* **108**:161–169. DOI: 10.1016/j.jhazmat.2004.02.014

Gee, GW, Or, D. 2002. Particle Size Analysis in: Dane, JH, Topp, GC (ed.), Methods of Soil Analysis. Part 4-Physical Methods. Madison: Soil Science Society of America

Harris, J.A., R.J. Hobbs, E. Higgs and J. Aronson. 2006. Ecological restoration and global climate change. *Restoration Ecology* **14**:170-176. DOI: 10.1111/j.1526-100X.2006.00136.x

Heneghan, L., S.P. Miller, S. Baer, M.A. Callahan Jr., J. Montgomery, M. Pavao-Zuckerman, C.C. Rhoades and S. Richardson. 2008. Integrating soil ecological knowledge into restoration management. *Restoration Ecology* **16**:608-617. DOI: 10.1111/j.1526-100X.2008.00477.x

Heras, J., P. Manas and Labrador, J. 2005. Effects of several applications of digested sewage sludge on soil and plants. *Journal of Environmental Science Health* **40**:437-451. DOI: 10.1081/ESE-200045646

Hobbs, R. J., and L. Atkins. 1988. Effect of disturbance and nutrient addition on native and introduced annuals in plant communities in the western Australia wheat belt. *Australian Journal of Ecology* **13**:171-179. DOI: 10.1111/j.1442-9993.1988.tb00966.x

Hornburg V., G. W. Brummer. 1993. Behavior of Heavy-Metals in Soils. *Zeitschrift Fur Pflanzenernahrung Und Bodenkunde* **156**:467-477.

Jorba, M., and P. Andrés. 2000. Effects of sewage sludge on the establishment of the herbaceous ground cover after soil restoration. *Journal of Soil and Water Conservation* **55**:322-327.

Jordan, W., M. E. Giplin, and J. D. Aber (Ed.). 1987. Restoration ecology: a synthetic approach to ecological research. Cambridge: Cambridge University Press.

Jordán, M.M., E. García-Sánchez, M.B. Almendro-Candel, F. Pardo, B. Vicente, T. Sanfeliu, J. Bech. 2017. Technosols designed for rehabilitation of mining activities using mine spoils and biosolids. Ion mobility and correlations using percolation columns. *Catena* **148**:74–80. DOI: 10.1016/j.catena.2016.02.027.

Jordán, M.M., S. Pina, F. García-Orenes, M.B. Almendro-Candel and E. García-Sánchez. 2008. Environmental risk evaluation of the use of mine spoils and treated sewage sludge in the ecological restoration of limestone quarries. *Environmental Geology* **55**:453-462. DOI: 10.1007/s00254-007-0991-4

Kleber, M., P. Nikolaus, Y. Kuzyakov and K. Stahr. 2000. Formation of mineral N (NH_4^+, NO_3^-) during mineralization of organic matter from coal refuse material and municipal sludge. *Journal of Plant Nutrition Soil Science* **163**:73–80. DOI: 10.1002/(SICI)1522-2624(200002)163:1<73::AID-JPLN73>3.0.CO;2-S

Knudsen, D, Peterson, GA, Pratt, PF. 1982. Lithium, Sodium, and Potassium in: Page, AL (ed.), Methods of soil analysis. Part 2. Chemical and microbiological properties. Madison: American Society of Agronomy, Soil Science Society of America. DOI: 10.2134/agronmonogr9.2.2ed.c13

Merlin, G., L. di Gioia, and C. Goddon. 1999. Comparative study of the capacity of germination and adhesion of various hydrocolloids used for revegetalization by hydroseeding. *Land Degradation and Development* **10**:21–34. DOI: 10.1002/(SICI)1099-145X(199901/02)10:1<21::AID-LDR318>3.0.CO;2-M

Moreno-Peñaranda, R., F. Lloret and J.M. Alcañiz. 2004. Effects of sewage sludge on plant community composition in restored limestone quarries. *Restoration Ecology* **12**:290-296. DOI: 10.1111/j.1061-2971.2004.00310.x

Morera, M.T., J. Echeverria, and J. Garrido. 2002. Bioavailability of heavy metals in soils amended with sewage sludge. *Canadian Journal of Soil Science* **82**:433– 438. DOI: 10.4141/S01-072

Navarro-Pedreno, J, M. B. Almendro Candel, M. M. Jordán Vidal, J. Mataix-Solera and E. García-Sánchez. 2004. Risk areas in the application of sewage sludge on degraded soils in the province of Alicante (Spain). *Geo-Environment* 293-302

Nelson, DW. 1982. Carbonate and Gypsum in: Page, AL (ed.), Methods of soil analysis. Part 2. Chemical and microbiological properties. Madison: American Society of Agronomy, Soil Science Society of America. DOI:10.2134/agronmonogr9.2.2ed.c11

Nelson, DW, Sommers, LE. 1982. Total carbon, organic carbon, and organic matter. in: Page, AL (ed.), Methods of soil analysis. Part 2. Chemical and microbiological properties. Madison: American Society of Agronomy, Soil Science Society of America. DOI:10.2134/agronmonogr9.2.2ed.c29

Ojeda, G, Alcañiz, JM, le Bissonnais, Y. 2008. Differences in aggregate stability due to various sewage sludge treatments on a Mediterranean calcareous soil. *Agriculture, Ecosystems and Environment* **125**:48–56. DOI: 10.1016/j.agee.2007.11.005

Ojeda, G., O. Ortiz, C. R. Medina, I. Perera & J. M. Alcañiz. 2015. Carbon sequestration in a limestone quarry mine soil amended with sewage sludge. *Soil Use and Management* **31**:270-278. DOI: 10.1111/sum.12179

Olsen, SR, Sommers, LE. 1982. Phosphorous in: Page, AL (ed.), Methods of soil analysis. Part 2. Chemical and microbiological properties. Madison: American Society of Agronomy, Soil Science Society of America. DOI: 10.2134/agronmonogr9.2.2ed.c24

Ortiz, O., and J. M. Alcañiz. 2006. Bioaccumulation of heavy metals in *Dactylis glomerata L.* growing in a calcareous soil amended with sewage sludge. *Bioresource Technology* **97**: 545-552. DOI: 10.1016/j.biortech.2005.04.014

Peñuelas, J., Sardans, J., Alcañiz, J.M., Poch, J.M. 2009. Increased eutrophication and nutrient imbalances in the agricultural soils of NE Catalonia (Spain) during the last four decades. *Journal of Environmental Biology* **30**: 841-846.

Pond, A.P., S.A. White, M. Milczarek and T.L. Thompson. 2005. Accelerated weathering of biosolid-amended copper mine tailings. *Journal of Environmental Quality* **34**:1293–1301. DOI: 10.2134/jeq2004.0405

Ram, LC, Srivasta, NK, Tripathi, RC, Jha, SK, Sinha, AK, Singh, G, Manoharan, V. 2006. Management of mine spoils for crop productivity with lignite fly ash and biological amendments. *Journal of Environmental Management* **79**:173–187. DOI: 10.1016/j.jenvman.2005.06.008

Ramírez, WA, Domene, X, Ortiz, O, Alcañiz, JM. 2008. Toxic effects of digested, composted and thermally-dried sewage sludge on three plants. *Bioresource Technology* **99**:7168-7175. DOI: 10.1016/j.biortech.2007.12.072

Rhoades, JD. 1982. Soluble Salts in: Page, AL (ed.), Methods of soil analysis. Part 2. Chemical and microbiological properties. Madison: American Society of Agronomy, Soil Science Society of America. DOI: 10.2134/agronmonogr9.2.2ed.c8

Singh RP, Agrawal, M. 2008. Potential benefits and risks of land application of sewage sludge. *Waste Management* **28**:347-358. DOI: 10.1016/j.wasman.2006.12.010

SOCIETY FOR ECOLOGICAL RESTORATION INTERNATIONAL SCIENCE & POLICY WORKING GROUP. 2004. The SER International Primer on Ecological Restoration. Tucson: Society for Ecological Restoration International.

Sopper, WE. 1993. Municipal Sludge Use in Land Reclamation. Boca Raton: Lewis.

Sort, X, Alcañiz, JM. 1996. Contribution of sewage sludge to erosion control in the rehabilitation of limestone quarries. *Land Degradation and Development* **7**:69-76. DOI: 10.1002/(SICI)1099-145X(199603)7:1<69::AID-LDR217>3.0.CO;2-2

Sort, X, Alcañiz, JM. 1999. Effects of sewage sludge amendment on soil aggregation. *Land Degradation and Development* **10**:3-12. DOI: 10.1002/(SICI)1099-145X(199901/02)10:1<3::AID-LDR305>3.0.CO;2-0

Tarrasón, D., G. Ojeda, O. Ortiz and J.M. Alcañiz. 2008. Differences on nitrogen availability in a soil amended with fresh, composted and thermally-dried sewage sludge. *Bioresource Technology* **99**:252-259. DOI: 10.1016/j.biortech.2006.12.023

Tedesco, M.J., E.C. Teixeira, C. Medina and A. Bugin. 1999. Reclamation of spoil and refuse material produced by coal mining using bottom ash and lime. *Environmental Technology* **20**:523–529. DOI: 10.1080/09593332008616848

Thomas, R. 2004. Practical Guide to ICP-MS. Maryland: Scientific Solutions

491
492 Verheijen, F.G.A., R.J.A. Jones, R.J. Rickson, C.J. Smith. 2009. Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews* **94**: 23-38. DOI: 10.1016/j.earscirev.2009.02.003
495

Tables

Table 1. General description of the mine sites located in the NE Iberian Peninsula

Quarry	Latitude (N)	Longitude (E)	Mean annual rainfall (mm)	Mean annual temperature (ºC)	Previous vegetation	Parent material
Aiguamolls	41º 28´ 31´´	0º 49´ 39´´	450-500	14-15	Shrubland dominated by *Thymus vulgaris* and *Rosmarinus officinalis* as dominant shrubs	Marl
Calvari	41º 30´ 26´´	0º 57´58´´	350-400	14-15	Rainfed tall fruit trees	Marl
Ponderosa	41º 15´ 41´´	1º 09´ 27´´	550-600	15-16	*Pinus halepensis* forest	Limestone
Antonieta	42º 16´ 06´´	1º 22´ 11´´	750-800	11-12	*Pinus nigra* forest	Limestone
Lázaro	41º 12´ 07´´	1º 28´ 57´´	500-550	15-16	*Pinus halepensis* forest	Limestone
Orpí	41º 31´ 22´´	1º 36´ 15´´	600-650	13-14	*Pinus halepensis* forest	Limestone
Montlleó	41º 41´ 35´´	1º 49´ 39´´	600-650	13-14	*Thymus vulgaris* and *Rosmarinus officinalis* shrubs	Sandstone
Vallcarca	41º 15´ 13´´	1º 52´ 25´´	500-550	15-16	Mixed forest: *Quercus ilex* and *Pinus halepensis*	Marl and limestone
Falconera	41º 15´ 40´´	1º 53´ 12´´	500-550	15-16	*Pinus halepensis* forest	Limestone
Cubetas	41º 20´ 24´´	1º 53´ 33´´	600-650	13-14	*Pinus halepensis* forest	Dolostone
Cuevas	41º 16´ 16´´	1º 54´ 13´´	500-550	15-16	*Quercus coccifera* shrubs	Limestone

Table 2. Analytical characterization of sewage sludges applied on the selected mine sites.

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
Stability degree (%)	48.1	60.1	31.8	17.2
Conductivity (dS m^{-1} 25ºC)	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^{-1})	36.8	63.4	11.5	19.8
N-ammonia (g kg^{-1})	10.7	21.5	1.8	7.3
P- total (g kg^{-1})	38.3	64.4	24.5	23.5
K (g kg^{-1})	2.8	5.7	1.0	1.5
Cu (mg kg^{-1})	322.3	580.0	102.0	170.6
Ni (mg kg^{-1})	23.0	43.3	15.5	13.9
Cr (mg kg^{-1})	56.6	85.6	12.5	35.7
Pb (mg kg^{-1})	54.3	64.2	29.5	28.1
Hg (mg kg^{-1})	2.0	4.2	0.2	1.3
Cd (mg kg^{-1})	3.7	10.0	0.9	3.6
Zn (mg kg^{-1})	1037.6	2199.0	375.0	512.6

Table 3. Summary of physical and chemical parameters of amended substrates (technosols). 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).

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 (1:5 extract w:v, dS/m 25ºC)	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

Table 4. Heavy metals concentration on amended soils and average and maximum increments relating to original mine spoils (nd: no detected; units: mg kg^{-1}). Z1, Z2 and Z3 refers to diverse slopes or zones in the same quarry. N=28.

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 EU (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

514 Table 5. Surface of soil affected by water erosion, erosion rates and soil loss on the
515 evaluated zones of quarries where soil erosion has been detected (Z1, Z2 and Z3 refer to
516 diverse slopes or zones in the same quarry).

Zone code	Affected area (m^2)	Erosion rate (Mg ha^{-1} $year^{-1}$)	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

517

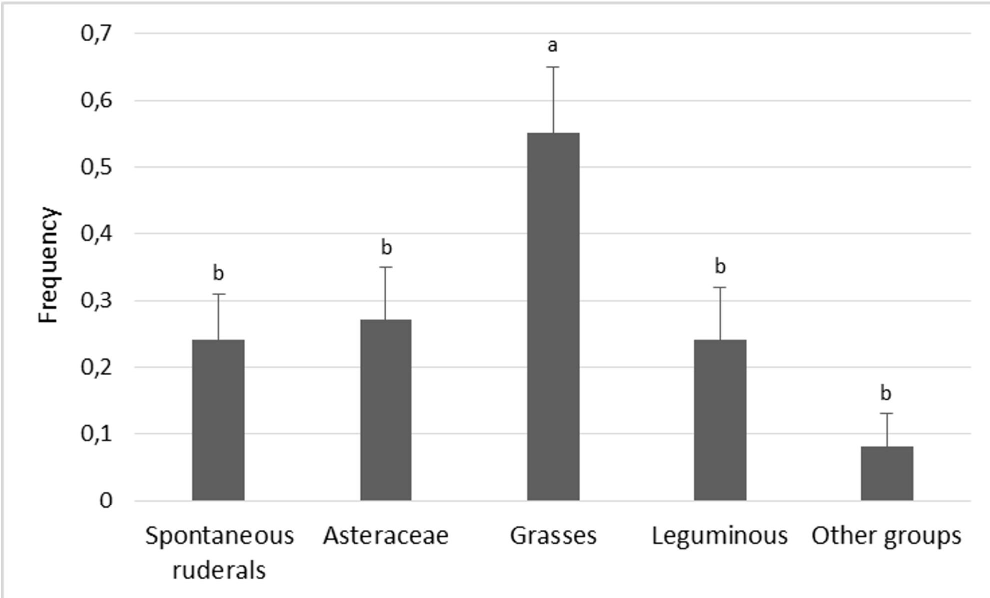

Figure 1. Frequency of different herbaceous plant functional groups in the evaluated zones of quarries. Error bars indicate standard error (P < 0.02).

1200x724mm (96 x 96 DPI)