Title: Soil restoration using compost-like-outputs and digestates from non-source-separated urban waste as organic amendments: limitations and opportunities

Authors: Carabassa, Vicenç [1,2*]; Domene, Xavier [1,2], Alcañiz, Josep M. [1,2]

Affiliations:

1 CREAF, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain.

2 Universitat Autònoma de Barcelona, E08193 Bellaterra (Cerdanyola del Vallès), Catalonia, Spain.

*Corresponding author: v.carabassa@creaf.uab.cat

Abstract

Soil rehabilitation in the context of the restoration of quarries, dumping sites, or road slopes often requires the prior addition of organic amendments to improve the substrates used for Technosol construction. Bio-wastes coming from advanced Mechanical-Biological Treatment Plants, mainly compost-like-outputs (CLO) and digestates (DGT), are new and suitable sources of organic matter potentially useful as organic amendments for this purpose, in an approach clearly fulfilling the principles of circular economy. In order to assess the suitability of these materials, a complete physicochemical and biological evaluation was carried out, including an ecotoxicological evaluation to discard hazardous effects on key soil fauna groups. Field experiments were also carried out on several road slopes and a dumping site. The stability degree of organic matter and the impurities content could be restricting parameters for the use of CLO in soils. Low stability degree decreased plant development in the initial stages of restoration. Moreover, the high heterogeneity in terms of physicochemical parameters of the different CLOs assessed is a serious constraint to making generalizations about its use. In contrast, composition of DGTs was more stable between plants and batches, and presented low impurities and high N contents that make them more suitable for applying to soil and promoting plant development. Regarding the application rates, DGT application at 20 $g \cdot kg^{-1}$ clearly improved plant growth after sowing, without compromising recruitment. However, application at 80 $g \cdot kg^{-1}$ did not ameliorate seed germination and plant growth, in either CLO or DGT treatments, and increased N-leaching and toxicity risk to soil mesofauna in DGT amended Technosols.

Keywords

Technosol, bio-wastes, Mechanical-Biological Treatment Plants, compost impurities, stability degree, ecotoxicity risk

1.Introduction

With global economic and social development, human activities like mining, road construction or landfilling have grown rapidly (Yang et al., 2016). As an example, mining activities occupy more than 1% of the Earth's surface and continue to grow (Šálek, 2012). These activities are usually developed in natural landscapes, producing severe impacts on all the ecological compartments, their ecological functions, and the ecosystem services that they provide to the society. In order to recuperate these services (or establish new ones), these spaces should be restored. The most common restoration practices include topographic modeling, spreading of a soil layer, and posterior vegetation establishment (Werner et al., 2001; Blanco and Lal, 2010).

In the context of restoration following these human activities, manufactured soils, so-called Technosols (Schad and Dondeyne, 2017), could be a viable restoration practice when the availability of suitable natural soils is limited (Watkinson et al., 2017). This technology is emblematic of the issues we face for the management of soils of the Anthropocene (Leguédois et al., 2016). The use of organic waste for Technosols construction is a widely used practice in soil restoration (Asensio et al., 2013; Lomaglio et al., 2017; Watkinson et al., 2017), shown to speed up the biological colonization of a relatively inert initial mineral substrate. Amendment properties of this organic waste are related to the ability of the contained organic matter to contribute in maintaining the soil humus and nutrient balance (Magdoff and Weil, 2004). This ability depends on the degradability of the organic matter, i.e. recalcitrance vs. labile organic fraction contents (Rumpel et al., 2002). Pedogenic processes occurring in Technosols are similar to those occurring in natural soils (Leguédois et al., 2016), although the ingredients used during their construction can strongly influence their evolution, the resulting soil properties and the capacity of the soil to provide ecosystem services. However, they tend to have a fast evolution compared to natural soils, including in terms of biological activity (Leguédois et al., 2016), which is a crucial factor for the provision of ecosystem services in soils (Tate, 2005) and a driver of soil pedogenesis (Frouz et al., 2013).

Approximately 120 to 140 million bio-waste tons are produced every year in the EU, which corresponds to approximately 300 kg per EU citizen per year (JRC, 2011). According to the Waste Framework Directive (EC, 2008), bio-waste corresponds to waste coming from gardens and parks, food and kitchen waste from households, restaurants,

caterers and retail premises, as well as the waste coming from food processing plants, therefore not including forestry or agricultural residues. Throughout Europe, about 40% of bio-waste is still landfilled (up to 100% in some Member States) (EC, 2010), a practice that is not in agreement with the guiding principles of EU Waste and Sustainable Resource Management Policy, notably the "waste hierarchy" that should underlie all national waste policies (JRC, 2011). According to a global circular economy perspective, the current European Union (EU) objectives aims for 65% of all municipal waste produced to be recycled before 2030, with only 10% disposed of in landfills (EC, 1999).

In an attempt to reduce the environmental impacts of biodegradable waste, mechanical and biological treatments are being used as a waste management process in many countries. Mechanical-Biological Treatment Plants (MBTP) attempt to mechanically separate the biodegradable and non-biodegradable components (Donovan et al., 2010). The non-biodegradable components are then sent for reprocessing or are landfilled, whereas the biodegradable components are reduced through composting (generating Compost-Like-Output, herein referred to as CLO) or by anaerobic digestion (generating digestate, herein referred to as DGT). Additionally, sometimes DGT is later composted obtaining compost from DGT (herein referred to as C-DGT).

The organic fractions of municipal solid waste are heterogeneous in terms of composition and source. The sustainable management of these waste products represent a challenge due to policy shifts and the increasing pressure on landfills (Abdullahi et al., 2008). If the recovery and biological treatment of bio-waste is properly performed, the resulting organic end-products may comply with quality requirements, while in other cases they can contain impurities (plastics, glass, metals) which might hamper their quality meaning that they do not fit local legislation or preventing their acceptance by the end-users.

The main goal of this article is to assess the limitations and opportunities of the use of CLO and DGT for Technosols construction in soil restoration works. The study considers this question at different scales, from the lab to the field, through a detailed characterization of waste products and their respective soil mixtures. This includes an ecotoxicological evaluation at the laboratory and greenhouse scale, and field trials in natural conditions.

2. Material and methods

2.1 DGT/CLO origin and characterization

The study was carried out in Catalonia (NE Iberian Peninsula), a region of 7 million people, representative of the Mediterranean EU, that produced 3.98 Tg of municipal solid waste in 2018 (ARC, 2019). Six of eight of the MBTP existing in Catalonia in 2016 were included in the study. The MBTP selection was carried out in order to include all of the variety of treated municipal organic waste products produced in these plants: three producing CLO (plant codes A, B, D), two producing DGT (plant codes C, F) and one producing C-DGT (plant code E). A composite sample of 15 kg of each batch, to be used for mixing with the soil, was taken from the respective MBTPs, taking sub-samples from different parts of the piles where batches were stocked. Samples were stored at 4ºC in plastic drums (2-3 days). Particle size and impurities content were determined in a 2 kg sample aliquot after drying at 60ºC for three days. For all MBTPs, sub-samples of each batch (1 kg) were sent, refrigerated in plastic bags, to external labs for a complete physicochemical characterization, shown in **Table S1**. In order to assess any seasonal variability of CLO composition, the MBTPs provided analytical information from representative samples obtained in different seasons and years (**Table S2**).

The characterization of CLO and DGT included the following parameters. Dry matter, pH, electrical conductivity (EC), organic matter, total nitrogen, ammonia-N, and the maturity test (Rottegrade) that were measured according to EN 13040 (2008), EN 13037 (2012), EN 13038 (1999), EN 13342 (2000), EN 13652 (2002), EN 13039 (2012), and EN 16087-2 (2012), respectively. Elemental analysis of P, K, Ca, Mg, Fe, Cd, Cr, Cu, Hg, Ni, Pb and Zn was carried out by ICP-OES according to ISO 11885 (2007) and EN 13650 (2002). Sample treatment consisted of drying at 110 ºC, grinding, calcination, acid digestion with 3N HNO_3 and filtration. Presence of pathogens (*Salmonella* and *E. coli*) was evaluated according to prEN 15215-1 (2006) and ISO 5679 (1997). Particle size distribution content was determined by dry sieving, and impurities by hand sorting, and reported as mass percentage (Huerta et al., 2010). The stability degree was measured as the non-hydrolyzable (stable) organic matter (percentage of organic matter remaining in the sample residue after an acid hydrolysis) as described in Huerta et al. (2010) and FCQAO (2002). This method removes the more labile fraction of an organic material, so the remaining organic material is considered as recalcitrant. The method consists of two consecutive steps of hydrolysis with sulfuric acid: the first one using acid at 72% at room

temperature where celluloses are hydrolyzed, and a second one using diluted acid at boiling point where other polysaccharides, proteins and lipids are hydrolyzed, with lignin and humic substances remaining.

2.2 Physicochemical, biological, and ecotoxicological characterization of DGT/CLO-soil mixtures

The Bw horizon of a clay-loam calcareous soil (Calcixerept according to Soil Survey Staff, 2014) was sieved to 5 mm and then mixed with respective CLO/DGT at increasing concentrations (0, 20, 80 $g \cdot kg^{-1}$). This amended soil intended to mimic the worst case in soil restoration, when topsoil is not available and more or less sterile mineral fractions are used (mining wastes, deep soil layers from constructions), requiring an organic amendment before its use for restoration purposes (see **Table 1**). The effect on soil water retention capacity was assessed gravimetrically. The organic matter content was determined through acid dichromate oxidation (Walkley-Black) and loss on ignition (American Society of Agronomy, 1982), and its quality by acid hydrolysis as described by Raya-Moreno et al. (2017). Microbial activity was assessed by measuring the basal respiration (Alef and Nannipieri, 1995). The soil pH (1:2.5 (w:v) soil:water extract) and salinity (as electrical conductivity of 1:5 (w:v) soil:water extract) were assessed according to the American Society of Agronomy Standards (1982). Finally, soluble elements were determined on 1:5 (w:v) soil:water extracts at the beginning and at the end of the experiment by ionic liquid chromatography (DIONEX®DX-100 Ion Chromatograph system).

To either evaluate the habitat function and the potential negative effects on plants of the selected organic amendments, the soil described above was mixed with each CLO or DGT. Thirty-nine pots (three per treatment) used as lysimeters were filled with about 2 kg of soil-organic amendments mixtures (at 0, 20, 80 $g \cdot kg^{-1}$). Pots were sown with wheat (*Triticum aestivum var Botticelli*), at a density of 176 $seeds \cdot m^{-2}$, and grown in controlled greenhouse conditions at an approximately stable moisture content (50% water holding capacity) for three months.

Table 1. Physicochemical characterization of the soil material (Bw horizon) used as substrate to be mixed with compost-like-outputs (CLO) and digestates (DGT) for laboratory and greenhouse experiments.

Parameter	Units	B horizon
Moisture 105ºC	%	1,3
pH (1:2.5 w:v)		8,47
Electrical conductivity (1:5 w:v, 25ºC)	dS/cm	0,128
Weight loss (375ºC)	%	2,5
Weight loss (550ºC)	%	4,0
Organic matter (W&B)	%	0,5
Resistant organic matter	% OM	62
Kjeldahl nitrogen (N)	%	0,032
Equivalent calcium carbonate	%	40
Clay D < 0,002mm	%	27,2
Fine silt0,002 < D < 0,02mm	%	50,8
Coarse silt 0,02 < D < 0,05mm	%	10,5
Sand 0,05 < D < 2mm	%	11,5
Texture class	USDA	CLAY LOAM
Cr	$mg \cdot kg^{-1}$	36,0
Ni	$mg \cdot kg^{-1}$	22,8
Pb	$mg \cdot kg^{-1}$	11,7
Cu	$mg \cdot kg^{-1}$	25,5
Zn	$mg \cdot kg^{-1}$	136,0
Hg	$mg \cdot kg^{-1}$	<0,4
Cd	$mg \cdot kg^{-1}$	<0,5

Seed germination was monitored for the first two weeks after sowing through direct observation, while plant elongation was determined monthly during the three months of the experiment, measuring all the germinated plants. Plant biomass was measured at the end of this period harvesting all the plants, weighing (wet weight), drying at 60ºC for three days, and weighing again (dry weight). After weighing, all the plant spikes were cut and weighed separately. All of the soil in each pot was dried and sieved at 2 mm before proceeding to the soil analysis.

In order to evaluate the habitat function and the ecotoxicological risks for soil fauna of the CLO/DGTs applications, the ISO 11267 survival and reproduction test of Collembola (*Folsomia candida*) (ISO, 1999) was performed. This test was applied to the same samples that were used in the plant bioassay, so the tested dosages were the same.

2.3 Field pilot tests

In order to upscale and test the suitability of CLO/DGT from MBTP as soil organic amendments in real restoration scenarios, three pilot field trials were carried out in different degraded land systems: a landfill slope (Lloret de Mar, LM) and two road slopes (Olost, OL and Terrassa, TE), located in a variety of Mediterranean climatic scenarios (**Table 2**) and soil types (**Table 3**). The organic waste amendments were mixed with the local soils at a dose of 20 $g \cdot kg^{-1}$, except for C-OL DGT, which was applied at a dosage of 40 $g \cdot kg^{-1}$ in the Olost site (**Table S3**). After mixing, the amended soil (30 -50 m^3) was spread in >50 m^2 plots (three plots per treatment) randomly distributed. The plots were sown using commercial seed mixtures adapted to the specificities of each area (see **Table S4**) at a density of 30 $g \cdot m^{-2}$.

Vegetation cover was monitored four, five and six months after soil seeding, taking orthogonal pictures of the plots and measuring soil covered by vegetation through ENVI image analysis software through photogrammetry. Plant biomass was determined by harvesting all the vegetation in 60 cm diameter circles randomly distributed in triplicate in each plot. Additionally, flora inventories were done by identifying all the species present in the plots, and species abundance was determined by qualitative observation of their respective cover. Soil sampling was done using an Edelman auger and taking 10 sub-samples of the first 20 cm of soil per plot just after amendment application (T0) and 4 months after (T1).

Table 2. Pilot test sites, type and location, climatic conditions (precipitation, temperature and Köppen class), slope characteristics (facing, landform, steepness and length) and organic waste tested (CLO= compost-like-output, DGT= digestate, C-DGT: compost-like-output from digestate).

Site	Restoration type	Latitude (N)	Longitude (E)	Mean annual precipitation (mm)	Mean annual temperature (°C)	Köppen-Geiger class	Facing	Landform type	Maximum slope (°)	Maximum slope length (m)	Organic waste type
Olost (OL)	Road slope	41° 59´ 4´´	2° 6´ 13´´	690	10,2	Cfa	W	Steeped slope	45	150	CLO, DGT and C-DGT
Terrassa (TE)	Road slope	41° 33´ 4´´	2° 0´ 4´´	620	14,8	Csa	NE	Steeped slope	43	80	DGT
Lloret de Mar (LM)	Landfill	41° 43´ 23´´	2° 51´ 2´´	650	14,5	Csa	SW	Steeped slope	33	50	CLO

Table 3. Physicochemical parameters of the soil materials used as substrate to be mixed with compost-like-outputs (CLO) and digestates (DGT) at the three pilot tests. Unamended substrate of Olost road slope (CNT-OL), of Terrassa road slope (CNT-TE) and Lloret de Mar landfill (CNT-LM).

Parameter	Units	CNT-OL (road slope)	CNT-TE (road slope)	CNT-LM (landfill)
pH		7,79	8,32	7,55
ELECTRICAL COND. AT 25ºC	dS/cm	1,385	0,166	0,093
TOTAL ORGANIC MATTER (W&B)	%	1,7	<0,50	<0,50
KJELDAHL NITROGEN (N)	%	0,117	0,021	<0,020
EQUIV. CALCIUM CARBONATE	%	31	19	3
CLAY D < 0,002mm	%	16,7	13,9	6,0
FINE SILT 0,002 < D < 0,02mm	%	24,6	20,7	7,5
COARSE SILT 0,02 < D < 0,05mm	%	13,8	14,9	4,7
SAND 0,05 < D < 2mm	%	44,9	50,5	81,8
TEXTURE CLASS	USDA	LOAM	LOAM	SANDY LOAM
Cr	$mg \cdot kg^{-1}$	25,5	17,4	<10,0
Ni	$mg \cdot kg^{-1}$	21,4	17,9	7,4
Pb	$mg \cdot kg^{-1}$	8,2	13,7	7,9
Cu	$mg \cdot kg^{-1}$	<20,0	20,9	<20,0
Zn	$mg \cdot kg^{-1}$	65,9	61,0	32,0
Hg	$mg \cdot kg^{-1}$	0,7	<0,4	<0,4
Cd	$mg \cdot kg^{-1}$	<0,5	<0,5	<0,5

2.4 Data analysis

Analysis of Variance (1 way-ANOVA and repeated measures ANOVA) was used to examine differences between treatments (0, 20, 80 $g \cdot kg^{-1}$) and waste types based on physicochemical characterization of soil mixtures (TOC, resistant C, soluble C, C-CO_2 respired), greenhouse experiment measurements (germination rate, plant height, plant and spike weight) and ecotoxicological risk assessment (survival and reproduction). Additionally a correlation analysis was done for chemical and ecotoxicological parameters of CLO/DGT mixtures. Regarding field pilot tests, differences in vegetation cover measures were examined between treatments and time. The cut-off for statistical significance throughout the manuscript was fixed at p=0.05.

3. Results

3.1 Suitability as organic amendments and comparison between CLO and DGT

A relatively high heterogeneity was observed in some analytical parameters (humidity, pH, conductivity, impurities, N-forms) between MBTP and between batches in the same plant (**Tables S1** and **S2**). Due to the fact that they had undergone very different treatments, CLO and DGT presented very different moisture contents: while the DGT had a dry matter content below 50%, CLO had a much lower humidity content, generally above 60% dry matter. Regarding salinity, clear differences between CLO and DGT were observed with higher EC values in CLO compared to DGTs, with the exception of CLO A that had an unusually low EC, particularly considering the values obtained from other batches of the same product (see **Table S2** for 2013 batches). However, at least for the batches included in this study (**Table S1**), electrical conductivity of CLO was less than 7 $dS \cdot m^{-1}$, with the exception of CLO D, that reached 9,2 $dS \cdot m^{-1}$.. Particle size distribution of the CLO samples (**Table S5**) showed a clear dominance of the fraction <2 mm, although large differences between the treatment plants were observed in this parameter. The main difference was the predominance (in volume) of a fibrous fraction in CLO A, mostly consisting of paper remains. There was also a notable contribution of the wood fraction greater than 10 mm in the C-DGT, which resulted from the structural material added for composting, consisting on pruning waste. Regarding DGT, the entire sample passed through a 2 mm sieve except some impurities, which were of a low proportion. This was mainly due to (1) the sieving process of the organic fraction performed before its digestion, which strongly reduced the impurities content and homogenized the organic matrix, and (2) to the anaerobic digestion that promoted a higher degradation (and fragmentation) of organic particles compared to aerobic stabilization. The relatively high impurities content in CLO D and F was mainly due to the presence of glass fragments (**Table S6**) that can be explained in CLO D by a failure in the sieving line as reported by MBTP engineers. Other analyses provided by this plant (see **Table S2**) showed an average value of impurities close to 5% in 2013 and 3% in 2014, although in 2013 one batch (January) reached 14%.

Regarding heavy metals, almost all the samples included in this study (except CLO D) are within the Spanish limit values for compost application to agriculture (BOE, 2013),

despite the fact that some of them exceed the EU end-of-waste limit values based on the 2008 IPTS pilot study on compost/digestate (IPTS, 2008), which are more restrictive (see **Table S7**).

In terms of organic matter contents, all the samples contained more than 40% in weight, as determined by loss-on-ignition (EN 13039, 2012). CLO A had a very high content, around 77%, probably due to fibrous paper pulp remains that are present in a high proportion as this MBTP receives noticeable amounts of this type of waste. On the contrary, C-DGT was the one with the lower content of volatile solids (48%), plausibly linked to the aerobic stabilization following the anaerobic digestion process. Maturity of CLO, measured with the Rottegrade test, showed a wide variation, from degree II (in CLO A) to V (in CLO B and C-DGT), sometimes showing higher stability (measured by acid hydrolysis) in less mature materials (CLO A vs CLO B). Wide variation in the ammonia-N contents was also measured, from 0.29% to 1.29%. (see **Table S1**).

3.2 CLO and DGT effects on soil properties

CLO and DGT increased soil water retention capacity when applied at 80 $g \cdot kg^{-1}$(see **Table S8)**, while such an effect was not detectable at lower dosages. At the same time, high dosage DGT treatments retained more water than CLO, especially in the case of C, where this trend was also detected at the low dosages (see **Table S8**). Both CLO and DGT are prone to increase soil EC due to the abundance of soluble compounds (see **Table S8**) resulting from the organic matter mineralization during their production at MBTP, but also after their application to soil (do Carmo et al., 2016). Just after application (EC_0) values were not very high, with the exception of CLO B, that reached 1.6 dS m^{-1} at the 80 g kg^{-1} dose. After three months of greenhouse incubation, EC tended to decrease in all the CLO treatments, while in DGT treated soils EC increased significantly, reaching relatively high values at the higher DGT C dosages (see **Table S8**). Regarding the composition of soluble elements in water extracts (**Table S9**), important differences existed between DGT and CLO. Nitrogen forms in digests treatments had a very high concentration of mineral nitrogen (nitrate, nitrite and ammonium) at the end of the greenhouse incubation (3 months), coupled to the conductivity increase, which can be attributed to the mineralization of the organic matter of the digest incorporated in the soil. In contrast, CLO treatments presented low soluble element contents, below those of controls. Concerning dose effects on soluble nitrogen forms, N immobilization was evident in CLO. While the initial mineral-N forms concentrations were clearly higher

than controls at the 80 $g \cdot kg^{-1}$ dosage, these concentrations became lower than controls three months after. The C-DGT had the lowest mineral-N concentrations (nitrite, nitrate, and especially ammonium). Concentrations of soluble phosphate were moderate in all the treatments, being the highest in the high dosage of CLO D (5.1 $mg \cdot kg^{-1}$), despite the fact that after three months digest C was the one with higher values (3.8 $mg \cdot kg^{-1}$). Furthermore, sulfate content also increased importantly after three months, agreeing with conductivity values. Similarly, sodium and chloride concentrations were high in all treatments at the high dose. Regarding the pH effects (see **Table S8**), the application of the CLO/DGT caused a slight acidification compared to controls (from 8.74 to 7.39).

As can see in **Figure 1**, TOC was above 2% in high application dosages except for the C-DGT. This case is probably due to its lower proportion of organic matter derived from the stronger stabilization process already mentioned. In fact, C-DGT had the highest proportion of acid hydrolysis-resistant organic carbon expressed on a TOC basis, and the lowest proportion of soluble C (**Figure 1**). C mineralization, assessed by basal soil respiration measurements, was inversely coupled with the content of resistant organic matter of the treated soils. CLO B presented the highest respiration rate (see **Figure 2**), while DGT C also showed high respiration rates during the first 15 days, and then decreased rapidly. DGT F and C-DGT presented the lowest respiration rates, in agreement with their low TOC and the proportionally high (referred to TOC) resistant organic matter content.

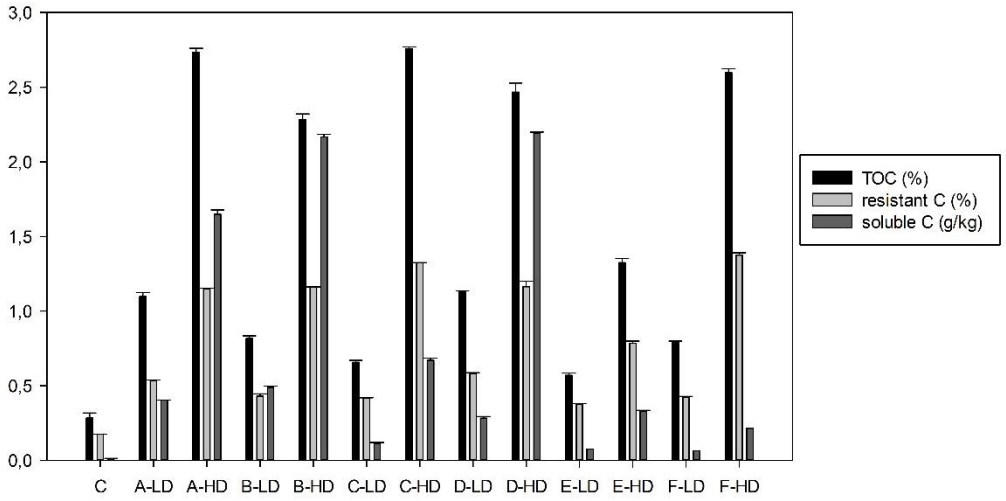

Figure 1. TOC (%), soluble-C ($g \cdot kg^{-1}$) and resistant C (%) in a soil amended with high doses (HD, 80 $g \cdot kg^{-1}$) and low doses (LD, 20 $g \cdot kg^{-1}$) of compost-like-outputs (CLO) or digestates (DGT). C: control; CLO: A, B, D; DGT: C, F; C-DGT: E. Error bars correspond to standard error. Letters indicate a significant difference between treatments according to Fisher's test ($p < 0.05$). n=39.

At the end of the incubation, respiration rates dropped to that of the control (<1 mg C-$CO_2 \cdot day^{-1}$), especially for the treatments with C-DGT and DGT F. Respiration rates in the controls were low and constant along the incubation time as expected, indicating the lack of mineralizable native carbon sources in this soil (see **Table S10**). Respiration rates for the less stabilized products (CLO A, CLO B, DGT C, CLO D) were high, and fitted a biphasic model. In the first phase, labile organic matter was fast mineralized and after this, respiration rate diminished (stabilization phase). In general, mineralization was globally high during the first 30 days (2.8 mg C-$CO_2 \cdot day^{-1}$, as average) and after this period remained stable (1 mg C-$CO_2 \cdot day^{-1}$ between 30 and 90 days). After the stabilization period, the less stabilized product (CLO B) respired almost 4 times more than the most stable one CLO (C-CLO) (see **Figure 2**).

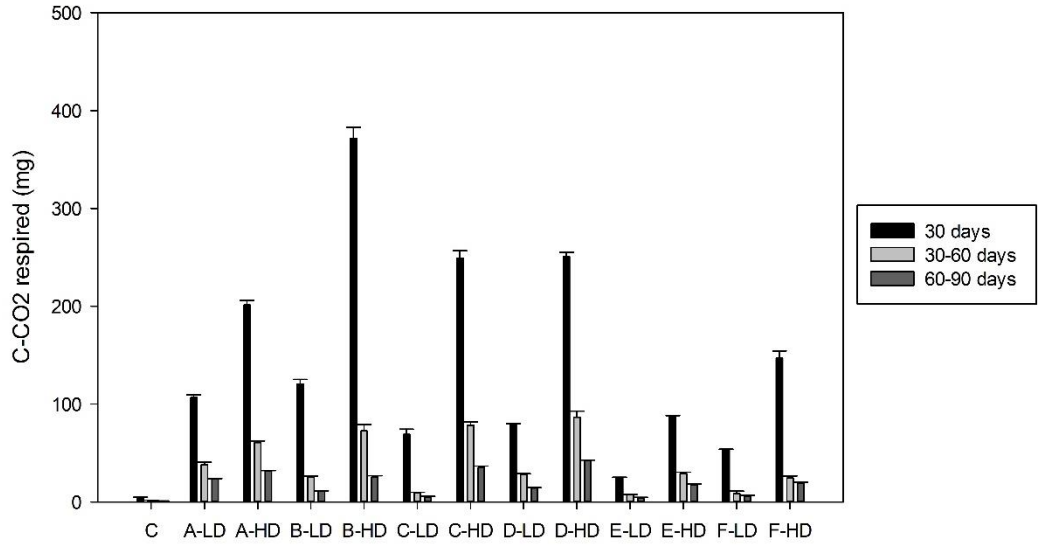

Figure 2. C-CO_2 respired (mg) over 90 days incubation in soil samples amended with high doses (HD, 80 g·kg^{-1}) and low doses (LD, 20 g·kg^{-1}) of compost-like-outputs (CLO) or digestates (DGT). C: control; CLO: A, B, D; DGT: C, F; C-DGT: E. Error bars correspond to standard error. Letters indicate a significant difference between treatments according to Fisher's test ($p < 0.05$). n=39.

3.3 Ecotoxicity risk assessment of CLO and DGT applications

Regarding plant germination, slightly higher rates were detected in both, C-DGT and CLO B, irrespective of the dosage and the salinity of the soil-organic residue mixtures (**Figure 3**). On the other hand, a slight germination inhibition effect was observed in CLO F at 80 g·kg^{-1} (F-HD).

In relation to plant growth, it is worth noting the satisfactory growth in DGT treatments and the poor development in the CLO ones (**Figure 4**). These differences were clearly observable at the first stages of development, one month after sowing, with a two-fold higher growth in DGT treatments than CLO ones, that were below the control level. Moreover, chlorosis was observed in controls and some CLO treatments at this stage. Such strong differences between CLO and DGT treatments after one month of sowing were mitigated at two months (see **Figure 4**), although DGT treatments were still showing more advanced plant development. The initial growth inhibition observed in CLO treatments was restricted to CLO D and A, although chlorosis of leaves was clear in all

the CLO treatments. Two months after sowing, controls and CLO treatments still presented chlorotic leaves, despite it being less marked in CLO than in controls. Aerial plant biomass corroborated the differences between CLO and DGT (see **Figure 5**). Spike biomass followed the same trends observed for total biomass, with DGT treated soils showing correct development of the spikes, while the treatments with CLO produced smaller spikes with lower number of seeds compared with the control (see **Figure 5**).

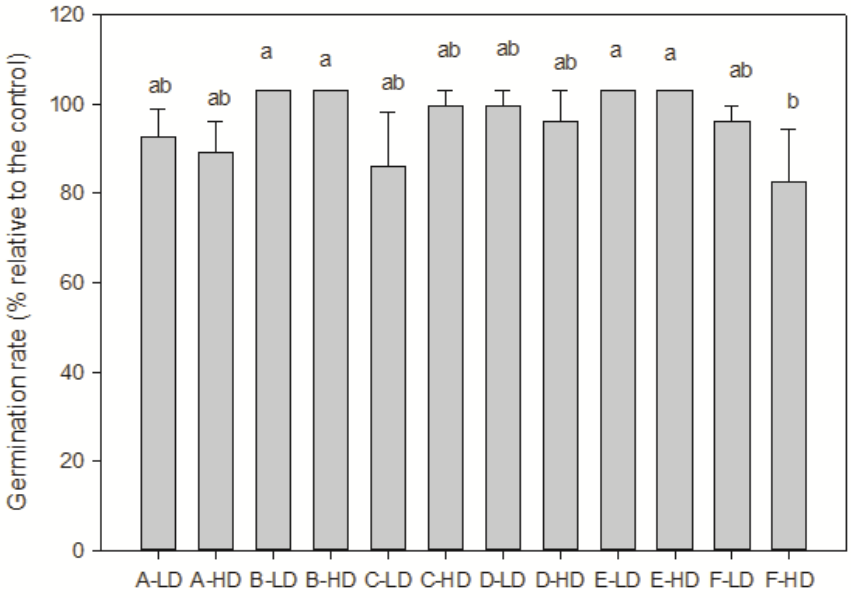

Figure 3. Wheat germination (%) relative to control, in soil samples amended with high doses (HD, 80 g·kg^{-1}) and low doses (LD, 20 g·kg^{-1}) of compost-like-outputs (CLO) or digestates (DGT). Treatment codes indicate the waste tested (CLO: A, B, D; DGT: C, F; C-DGT: E) and dose (HD: 80 g·kg^{-1}; LD: 20 g·kg^{-1}). Error bars correspond to standard error. Letters indicate a significant difference between treatments according to Fisher's test ($p < 0.05$). n=39.

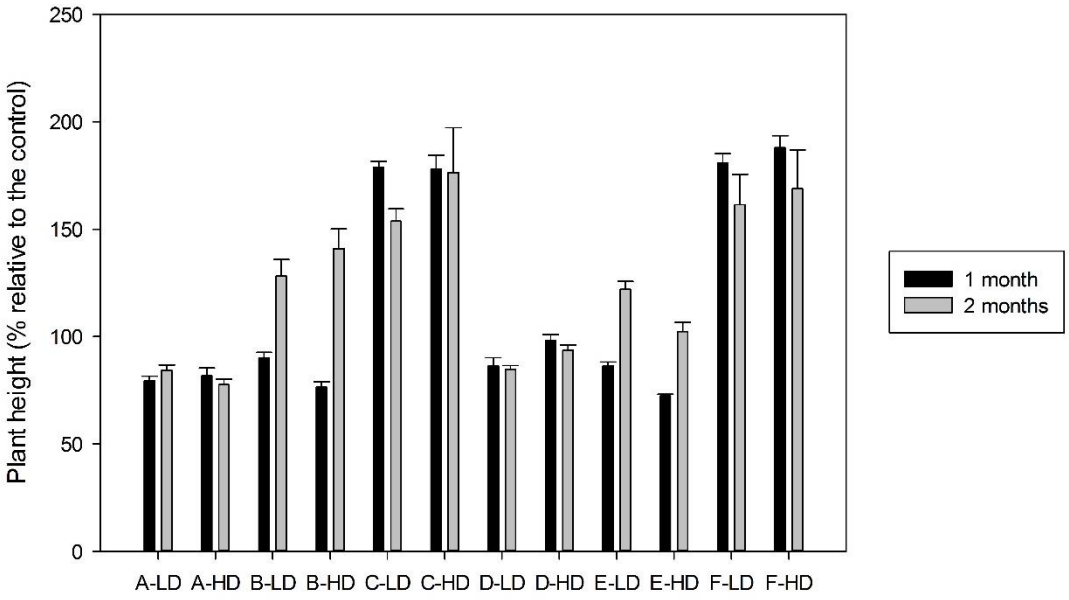

Figure 4. Height of wheat plants growth in CLO/DGT amended soil, relative to the control, as a function of the applied treatment, one month and two months after sowing. The treatment codes indicate the waste tested (CLO: A, B, D; DGT: C, F; C-DGT: E) and dose (HD: 80 $g \cdot kg^{-1}$; LD: 20 $g \cdot kg^{-1}$). The error bars correspond to standard error. The letters indicate a significant difference according to Fisher's test ($p < 0.05$). n=78.

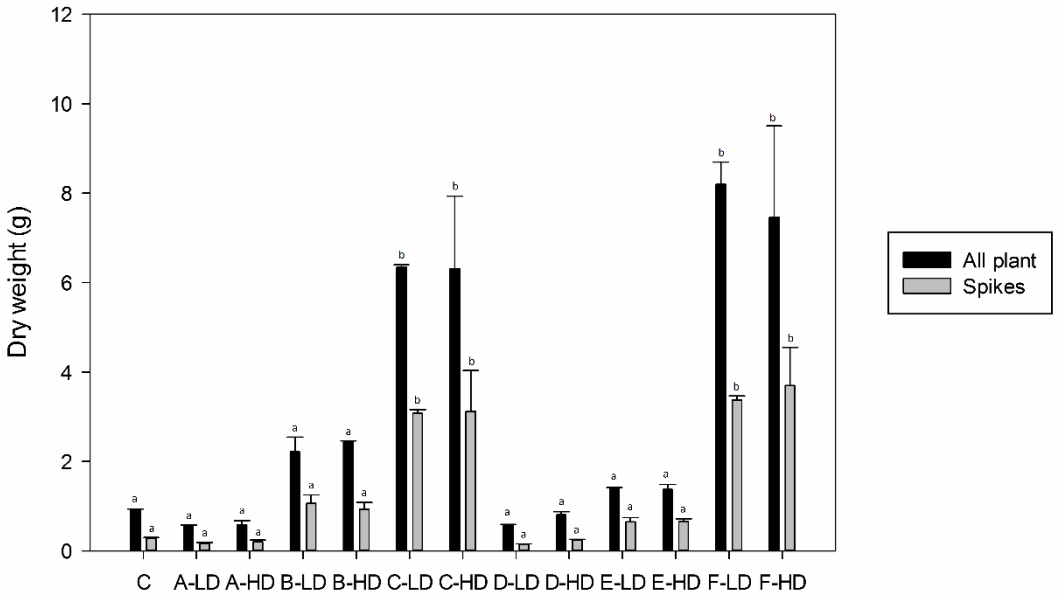

Figure 5. Total biomass and spike biomass (dry weight) of wheat plants growth in CLO/DGT amended soil, depending on the applied treatment. Treatment codes indicate the waste tested (CLO: A, B, D; DGT: C, F; C-DGT: E) and dose (HD: 80 $g \cdot kg^{-1}$; LD: 20 $g \cdot kg^{-1}$). The error bars correspond to standard error. The letters indicate a significant difference according to Fisher's test ($p < 0.05$). n=39.

Soil collembolan (*F. candida*) survival in DGT/CLO-soil mixtures after 28 days showed a clear effect of CLO B mixtures when applied at high doses (see **Figure 6**). While DGT low dosages were neutral or led to survival promotion over controls, differences with CLO A (LD), E (LD) and D were not statistically significant. These results were consistent with those obtained when *F. candida* reproduction was assessed (see **Figure 6**). All of the CLO treatments, with the exception of CLO E, exhibited very strong reproduction inhibition at the high dosage. In CLO B, this inhibition was due to the mortality of adult individuals, while in CLO A and D, no significant mortality was detected. Inhibition of reproduction was also explained by chronic toxicity of decomposition products or other unassessed substances in these residues (Domene et al., 2007), or by salinity, slightly coupled to these reproductive effects (**Table S11**). The

correlation with the stability degree of the amendments becomes more evident looking at the results in the C-DGT treatment, the most stable material included in this study, where no inhibition on reproduction was observed.

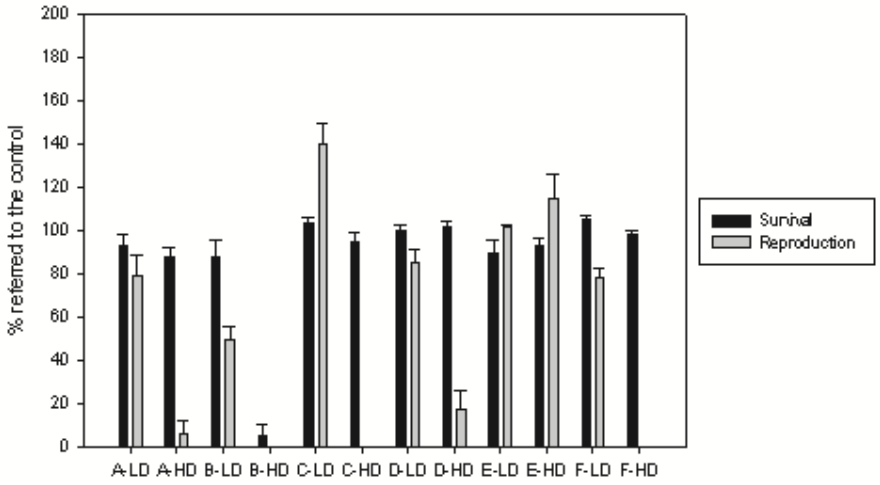

Figure 6. Survival and reproduction rates of *Folsomia candida* in CLO/DGT amended soil, relative to the control, depending on the applied treatment. Treatment codes indicate the waste tested (CLO: A, B, D; DGT: C, F; C-DGT: E) and dose (HD: 80 $g \cdot kg^{-1}$; LD: 20 $g \cdot kg^{-1}$). The error bars correspond to standard error. The letters indicate a significant difference according to Fisher's test ($p < 0.05$). n=65.

3.4 Upscaling to the field: CLO and DGT applications for soil restoration purposes

One month after the setup of the plots, all treatments showed higher herbaceous cover than controls, except for some treatments in the road slopes of Olost (A-OL and B-OL). Moreover, A-OL and B-OL presented vegetation covers below controls of Terrassa road slope and Lloret de Mar landfill (CNT-TE and CNT-LM, respectively) which are much more unfertile than CNT-OL. Four months after the spreading of the technosols on the slopes, plots with an application rate of 20 $g \cdot kg^{-1}$ of DGT showed almost two-times more vegetation cover than controls (**Figure 7**). This difference was even bigger when control soils were extremely poor in organic matter and nutrients, such as those in TE. Regarding the CLO treatments, their effects were dependent on the quality of control soil: in

relatively fertile ones like OL, all the CLO treatments showed a lower plant cover development than controls, especially A-OL and D-OL, which after four months resulted in plots without vegetation. In contrast, in very poor soils (LM) the CLO application promoted vegetation development.

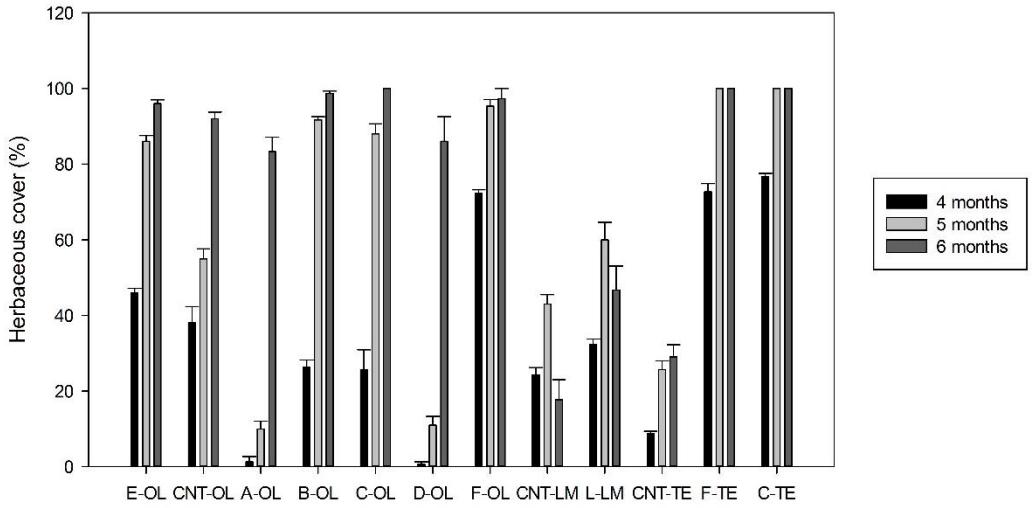

Figure 7. Herbaceous cover on plots restored with soil amended with CLO/DGT, 4, 5 and 6 months after Technosol spreading. Treatment codes indicate the waste tested (CNT: control; CLO: A, B, D; DGT: C, F; C-DGT: E) and the site (OL: Olost; Te: Terrassa: LM: Lloret de Mar). The error bars correspond to standard error. The letters indicate a significant difference according to Fisher's test ($p < 0.05$) between measures of the same site. n=36.

Regarding differences between doses, treatment with 40 $g \cdot kg^{-1}$ of digest (C-OL) presented less vegetation cover than treatment with 20 $g \cdot kg^{-1}$ (E-OL) on the first sampling. Regarding EC, this increased after applying the amendment and diminished after five months (see **Tables S12** and **S13**).

Looking at plant biodiversity, during the first months after soil restoration (**Tables S14, S16 and S17**), sown species dominated in all the plots, controls and amendments. Biodiversity was relatively low in all the sites and treatments, with the plots in Terrassa being the richest, with more than 50 species identified, mainly from Asteraceae, Fabaceae and Poaceae families. In control plots a relative dominance of leguminous was observed, mainly in very poor soils, such as those in Terrassa and Lloret de Mar. In DGT and CLO

amended plots, a dominance of seeded grasses was observed during the first months after soil restoration (**Tables S14, S16 and S17**), although at the mid-term (ten months), ruderal vegetation increased, being dominant in some plots (**Table S15 and S17**). However, ruderal plants differed between treatments: in DGT plots, species typical from nitrogen rich environments (*Chenopodium sp., Cardus sp.*) were observed.

4. Discussion

Results relating to CLO and DGT characterization showed a high variability between products of different plants, and batches of the same plant. However, it is possible to clearly distinguish between DGT and CLO amendments, which have very different characteristics. Regarding DGT, a general pattern of relatively high moisture, low EC and homogeneous particle size distribution has been detected. Despite low EC and homogeneous particle size distribution being positive factors for the use of DGT, high moisture content (>80%) could cause technical problems such as difficulties for transporting and handling, and the production of leachates (Alcañiz et al. 2009).

Regarding CLO, impurities content seemed to be the main restricting factor for their application at soil. It is worth noticing that small impurities (below 2 mm) could be underestimated by the available current methodologies, so the total proportion of impurities could be even greater. Regarding the type of impurities, glass and plastics were those found in a greater proportion (in weight), and moreover, plastics represented a significant volume. These are relevant features in terms of public acceptance as those materials cause strong visual impacts, especially for glass particles due to its ability to reflect light. However, the most important issue is of the currently known negative (direct and indirect) effects of plastics (including microplastics) on trophic networks, and more specifically on soil organisms (Huerta Lwanga et al., 2016; Zhu et al., 2018). As expected, the CLO had higher concentrations of heavy metal content than the compost obtained from source-separated bio-waste in Spain (ESAB, 2005) and in European countries (Saveyn & Eder, 2014), however the analyzed CLO would still be able to be applied to agricultural soils according to Spanish law (BOE, 2013).

Despite EC values being higher than DGT, in general EC was not a critical factor for the use of CLO as an organic amendment, except for CLO D, which had a conductivity above 9 $dS \cdot m^{-1}$. One hand, a germination stimulation was not observed in either treatment,

despite some stimulation having been described previously after the application of mature compost to soil (Abdullahi et al., 2008). On the other hand, an inhibition effect was observed for some CLO, but because all the treatments had a germination rate higher than 80% (compared to the control) any phytotoxic effect was discarded (McLachlan et al., 2004). In any case, the use of CLO with conductivity higher than 9 $dS \cdot m^{-1}$ could cause germination inhibition in sensitive plants at high to medium application rates such as those used for Technosol construction in road slopes or other soil rehabilitation efforts (do Carmo et al., 2016; Evenari, 1949). Moreover, after applying the amendments to soil, EC could increase due to mineralization of the organic matter, despite the fact that in the greenhouse experiment, soils treated with CLO showed an EC reduction. This is due to both an immobilization effect of soluble elements on minerals or on microbial biomass, and through losses by leaching or plant uptake (Raviv et al., 2019). High sodium and chloride concentrations could be explained by the domestic origin of the organic wastes (Domene et al., 2007).

The low soluble element contents in the CLO treatments can be explained by the immobilization effect, where nitrogen is immobilized as microbial biomass (Bastida et al., 2008; Davidson et al., 2013). The application of low stability wastes to soil increases microbial activity in the short-term (Bastida et al., 2008; Meena et al., 2016), but leads to sequestering (immobilizing) of nutrients, since the amount of plant-available N from municipal solid waste is closely related to the degree of compost maturity (Crecchio et al., 2001) and stability (Davidson et al., 2013; Tarrasón et al., 2008). This trend was stronger at higher dosages of CLO that showed lower plant growth than at the lower dosages. This effect also explains the chlorosis and the poor plant development observed in some CLO treatments in the greenhouse experiment that increased at high dosages since more labile carbon was present and promoted this unintended effect on growth. This effect also affected spike biomass, which was taken as a proxy of the reproductive effort or seed output (Bazzaz et al., 1992; Reekie and Bazzaz, 2002), but is also a key ecological parameter directly linked to seed bank establishment capacity in natural environments and indicative of the potential recovery of the herbaceous cover after a disturbance (Reekie and Bazzaz, 2005, 2002). Moreover, toxicity against *F. candida* observed in CLO B mixtures when applied at high doses could be due to the release of decomposition products such as ammonium, phenols or organic acids (Domene et al., 2007), or other toxic compounds (Andrés and Domene, 2005; Crouau et al., 2002) inherited from the

residue. Since the CLO B treatment also showed the highest salinity contents in soil mixtures (see section 3.2), this parameter could also partially explain the negative effect observed (Domene et al., 2007). However, in any case salinity was not the main reason because other treatments that were similar in terms of salinity did not show toxicity.

In the controls, soil chlorosis could be explained by the low concentration of plant-available N in the B horizon material. In C-DGT treatments the low mineral-N concentration was due to the double-stabilization process (anaerobic digestion and composting) carried out for this material, since anaerobic digestion mineralizes the more labile organic matter and releases ammonium-N, which can then be easily lost as ammonia in the composting phase (Himanen and Hänninen, 2011). In contrast, in the treatments with DGT (both high and low doses), the high concentration of nutrients (nitrates and phosphates, see section 3.2) boosted plant development. Biomass production did not differ significantly between the dosage range studied (20-80 $g \cdot kg^{-1}$), indicating that low dosages are also within the plant requirements and that higher rates might be unnecessary. Therefore, high dosages should be avoided in order to prevent the negative environmental effects of leaching of soluble elements provided by the organic amendments but not taken by plants (Logan and Visvanathan, 2019).

Despite all materials having organic matter with a high stability degree (>40%), as determined by acid hydrolysis, measuring stability with a single parameter gives limited information (Morel et al. 1985; Reinikainen and Herranen, 2001; Komilis and Tziouvaras, 2009) since different factors could affect this measure. The stability degree values were correlated with C:N ratio, with DGT C being the one with the lowest value (<12). This might have modified the soil microbiological equilibrium, as C:N was below the 12-15 range (Bernal et al., 1998), favoring N losses. However, some authors have criticized the use of the C:N ratio as an indicator parameter for compost stability and maturity (Wu et al., 2010; Tiquia et al., 2000). Maturity measured through the Rottegrade test is highly influenced by the sample heterogeneity (Weppen, 2002) that may have been very high in some CLO samples in terms of composition and particle size distribution. Moreover, as stated by Huerta et al. (2010), the Rottegrade test is not a suitable method for evaluating maturity of DGT, and a combination of both stability degree and biological stability could give an idea about the potential for DGT to act as organic amendment (Tambone et al., 2009). Regarding ammonia-N content, no correlation was observed between temperature (Rottegrade test), and neither with stability degree, despite ammonia-N content also being

considered as a good indicator of low maturity of compost (Bernal et al., 1998; Clemente et al., 2006; Tiquia et al., 2000).

Despite differences, both products were dominant in the fraction below 2 mm, which is of interest as it is this fraction that is mostly responsible for the organo-mineral interactions in soil, and consequently for the aggregate formation and preservation of organic carbon (Jones and Singh, 2015), a key issue in the improvement of soil fertility globally. Moreover, a relatively fast and direct effect of the application of organic amendments to soil was the improvement of structure, which enhanced the water retention capacity (Ojeda et al., 2011, 2010). This effect could be observed in the highest application dosages, either in CLO and DGT, but not in low dosages, probably due to the clay loam texture of the experimental soil used. At the same time, DGT seemed to have a better capacity to improve soil structure, due to the deep effect on soil structure conferred by digestates (Ojeda et al., 2011, 2010). Moreover, the slight acidification observed in both treatments could be considered positive, though soil remained basic due to its calcareous nature.

Differences between CLO and DGT observed at laboratory and greenhouse scales were also observed at the field plots and were even stronger when comparing the effects of those amendments in poor soils (CNT-LM and CNT-TE). Soils amended with CLO presented lower vegetation than soils amended with DGT. According to the results at greenhouse scale, these differences could be mainly explained by the high N content of DGT and the lower stability of CLO. Regarding biodiversity, despite the dominance of ruderal and sown species in amended plots, recruitment of weeds and shrubs was observed in all the sites, for which we should think, in accordance with other studies that the use of these organic amendments at moderate doses would not negatively affect plant recruitment and diversity in the mid-term (Carabassa et al., 2018).

Conclusions

Low stability degree and high impurities content are the most restricting parameters for applying CLO to soils. Furthermore, there is a considerable heterogeneity of CLO produced by different plants and also between different batches of the same plant, in relation to the main physicochemical parameters considered, which is a constraint to making generalizations about CLO use. In contrast, DGT composition is more stable

between plants and batches. DGT presents low impurities and high N content that makes it more suitable for applying to soil and promoting plant development and growth. Regarding dosage, doses higher than 20 $g \cdot kg^{-1}$ do not improve vegetation development and growth, neither in CLO or DGT, and increase environmental problems associated with the use of organic wastes, such as water pollution and toxicity to soil fauna.

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Supplementary materials

Table S1. Physicochemical and microbial characterization of selected CLO and DGT.

MBTP plant code	A	B	C	D	E	F
Material type	CLO	CLO	DGT	CLO	C-DGT	DGT
Dry matter (% fresh matter at 105 ºC)	66	70	25,4	65	68,1	32,3
pH	8,16	7,21	8,35	8	8,06	8,77
Electrical conductivity 25ºC ext 1:5 (dS/m)	1,66	6,75	3,88	9,2	6,85	3,26
Amonia-N (% dry matter)	0,29	0,25	1,29	0,48	0,39	0,95
Kjeldhal-N (% dry matter)	1,8	2,17	3,1	1,4	2,09	3,02
Organic matter (% dry matter)	64	45,5	64,6	44	55,7	50,7
Stability degree (% of OM)	52,8	46,5	44,5	47,8	60,1	57,4
C/N ratio	18	13,4	10,4	13	13,3	14,2
Rottegrade class	II	V	-	IV	V	-
P (% sms)	0,3	1,22	0,87	0,42	0,611	1,2
K (% sms)	0,59	1,07	0,77	0,63	1,26	0,78
Ca (% sms)	3,8	9,2	6,66	5,1	8,9	8,7
Mg (% sms)	0,49	1,05	0,825	0,561	0,795	1,43
Fe (% sms)	0,43	0,77	2,33	0,56	0,89	0,95
Cd(mg/kg)	1,1	1,13	1,98	1,9	0,94	1,05
Cu (mg/kg)	171	259	129	106	219	156
Ni (mg/kg)	35	23,7	33,4	182	19,2	27
Pb (mg/kg)	82	71,6	87,6	57	76,8	107,3
Zn (mg/kg)	302	426	372	190	415	463
Hg (mg/kg)	2	0,42	1,92	0,27	<0,40	1,03
Cr (mg/kg)	67	30,7	79	461	28,8	62
Salmonella (in 25g)	0	0	0	0	0	0

Table S3. Organic waste types and doses tested on pilots trials (CLO= compost-like-output, DGT= digestate, C-DGT: compost-like-output from digestate). Olost road slope (OL), Terrassa road slope (TE) and Lloret de Mar landfill (LM).

Site code	Organic waste type	Organic waste code	Application dose (g/kg)
OL	CLO	A	20
OL	CLO	B	20
OL	DGT	C	40
OL	CLO	D	20
OL	C-DGT	E	20
OL	DGT	F	20
LM	CLO	L	20
TE	DGT	C	20
TE	DGT	F	20

Table S4. Composition and proportion of the seed mixtures sowed on the pilot tests. Olost road slope (OL), Terrassa road slope (TE) and Lloret de Mar landfill (LM).

Species	**Seed proportion OL (%)**	**Seed proportion TE (%)**	**Seed proportion LM (%)**
Lolium rigidum	28,50	0	0
Melilotus officinalis	29,50	0	0
Lolium perenne	0	30	20
Festuca arundinacea	0	20	20
Agropyrum cristatum	14,25	10	15
Dactylis glomerata	0	20	15
Paspalum notatum	0	0	10
Cynodon dactylon	9,50	5	5
Eragrostis curvula	0	0	5
Medicago sativa	14,25	5	5
Onobrychis viciifolia	0	10	5
Plantago lanceolata	2,00	0	0
Asphodelus fistulosus	1,25	0	0
Moricardia arvensis	0,75	*0*	0

Table S5. Particle–size distribution (% dry matter) of the compost-like-outputs included in this study.

MBTP Plant code	>10 mm (%)	10-5 mm (%)	5-2mm (%)	<2mm (%)
E	2,1	4,5	14,4	79,1
A	1,2	0,5	42,0	56,3
B	0,3	2,8	31,3	65,6
D	0,1	5,4	15,5	79,0

Table S6. Impurities >2 mm (% dry matter) in the compost-like-outputs and digestates included on this study. (A, B, D: compost-like-outputs; C, F: digestates; E: compost-like-output from digestate).

MBTP Plant code	E	A	B	D	C	F
Stones (%)	0,0	0,0	0,0	0,5	0,0	0,0
Glass (%)	0,4	0,5	0,3	3,0	0,0	0,0
Plastics (%)	0,9	1,1	0,2	0,8	0,4	0,3
Metals (%)	0,1	0,4	0,2	0,0	0,0	0,0
Total (%)	1,4	2,1	0,7	4,3	0,4	0,3

Table S7. Heavy metal contents of different compost-like-outputs (CLO), digestates (DGT) and composted digestates (C-DGT) compared to those compost segregated at source produced in Spain (ESAB, 2005), the maximum values for EU EoW product quality criteria (IPTS, 2008) and for agricultural uses in Spain (BOE, 2013). *Source-Segregated.

MBTP plant code	**Material type**	**Cd (mg/kg)**	**Cu (mg/kg)**	**Ni (mg/kg)**	**Pb (mg/kg)**	**Zn (mg/kg)**	**Hg (mg/kg)**	**Cr (mg/kg)**
A	CLO	1,1	171	35	82	302	2	67
B	CLO	1,13	259	23,7	71,6	426	0,42	31
C	DGT	1,98	129	33,4	87,6	372	1,92	79
D	CLO	1,9	106	182	57	190	0,27	461
E	C-DGT	0,94	219	19,2	76,8	415	<0,4	29
F	DGT	1,05	156	27	107,3	463	1,03	62
ESAB, 2005	Spanish SS* compost	0,35	103	36	54	215	0,88	32
EU EoW quality criteria (IPTS, 2008)	Compost and digestate	1,5	200	50	125	600	1	100
Spanish límits for agricultural uses (BOE, 2013)	Compost	3	400	100	200	1.000	2,5	300

Table S8. Water holding capacity (WHC), increment of WHC relative to the control soil (ΔWHC), pH and EC evolution of the soil amended with two doses of DGT/CLO (CLO= compost-like-output, DGT= digestate, C-DGT: compost-like-output from digestate). EC_0= electrical conductivity just after applying the DGT/CLO; EC_3= electrical conductivity three months after applying the DGT/CLO.

MBTP plant code	**Organic waste type**	**Dose ($g \cdot kg^{-1}$)**	**Saturation humidity (%)**	**WHC (%)**	**ΔWHC (% refereed to control)**	**pH**	**EC_0 25ºC $\mu S\ cm^{-1}$**	**EC_3 25ºC $\mu S\ cm^{-1}$**
CONTROL	-	0	57	55	-	8,74	128	199
A	CLO	80	73	71	15	7,89	1293	695
A	CLO	20	55	53	-2	8,14	563	292
B	CLO	80	74	70	14	7,44	1578	722
B	CLO	20	61	59	4	7,93	588	338
C	DGT	80	84	81	26	7,39	1281	1931
C	DGT	20	64	63	7	8,18	323	723
D	CLO	80	74	71	16	7,80	1336	759
D	CLO	20	59	55	0	8,14	456	346
E	C-DGT	80	73	71	15	8,16	825	828
E	C-DGT	20	57	55	0	8,41	288	286
F	DGT	80	79	76	20	7,9	912	1174
F	DGT	20	60	59	3	8,3	326	402

Table S9. Soluble elements concentration in a soil amended with compost-like-outputs and digestates just after mixing (0) and after three months of incubation in greenhouse conditions (3). Units: $g \cdot kg^{-1}$ (dose); $mg \cdot kg^{-1}$ (soluble elements). (A, B, D: compost-like-outputs; C, F: digestates; E: compost-like-output from digestate).

MBTP plant code	DOSE	TIME	Cl^-	NO_2^-	NO_3^-	PO_4^{3-}	SO_4^{2-}	Na^+	NH_4^+	K^+	Mg_2^+	Ca_2^+
CONTROL	0	0	24	2,7	7	1,9	49	39	0,9	4	7	341
CONTROL	0	3	79	1,1	11	1,6	70	83	3,8	3	1	347
A	80	0	668	1,4	2	4,0	734	574	24,4	103	159	2441
A	80	3	497	1,2	3	3,3	328	471	0,9	22	28	834
A	20	0	251	4,0	8	2,0	276	230	2,9	23	29	1112
A	20	3	179	1,7	4	1,3	109	169	2,9	7	14	515
B	80	0	538	0,1	10	1,7	648	402	24,3	104	60	3316
B	80	3	553	2,4	110	2,5	364	410	2,3	25	14	863
B	20	0	171	2,4	4	2,3	254	151	5,1	19	nd	1351
B	20	3	208	1,4	20	2,0	156	155	1,8	9	15	522
C	80	0	826	1,4	8	2,1	258	346	246,8	115	nd	1583
C	80	3	786	14,7	1041	3,8	3216	425	82,0	77	118	3917
C	20	0	175	0,4	4	3,5	72	88	0,0	8	4	511
C	20	3	447	1,0	898	0,7	903	249	1,2	12	40	1928
D	80	0	637	0,3	2	5,1	538	483	16,5	75	nd	2499
D	80	3	602	1,7	2	1,1	468	441	0,0	21	31	787
D	20	0	205	2,8	18	1,3	124	163	0,6	9	12	476
D	20	3	187	3,2	6	3,7	194	158	2,5	11	nd	975
F	80	0	415	2,7	1	0,8	343	346	147,7	80	29	986
F	80	3	407	13,8	2075	3,5	385	385	1,0	26	58	1987
F	20	0	173	2,0	3	1,5	138	122	1,9	20	1	561
F	20	3	201	1,2	251	2,0	267	196	0,1	7	2	706
E	80	0	849	0,3	4	0,1	278	452	3,1	87	nd	1065
E	80	3	1037	0,4	10	0,8	275	513	0,1	35	39	910
E	20	0	176	1,5	2	1,3	97	129	1,2	6	nd	578
E	20	3	201	1,9	7	1,0	87	143	0,7	11	10	388

Table S10. Respiration rate evolution (mg C-CO2 · day-1) during the 12 weeks of incubation, according to the treatment. (A, B, C, D, E, F: DGT/CLO ID; HD, 80 g·kg-1; LD, 20 g·kg-1).

Treatment	Week 1	Week 2	Week 4	Week 8	Week 12
C	0,30	0,19	0,14	0,03	0,03
A-LD	4,66	4,44	2,27	1,34	1,02
A-HD	7,32	8,09	5,55	2,21	1,36
B-LD	6,20	4,90	2,18	0,97	0,47
B-HD	7,32	15,35	12,68	2,95	1,11
C-LD	4,16	2,69	1,03	0,35	0,21
C-HD	7,32	14,50	5,95	2,92	1,53
D-LD	3,57	2,64	1,75	1,06	0,62
D-HD	7,32	10,19	6,84	3,28	1,85
E-LD	1,24	0,83	0,57	0,27	0,17
E-HD	4,07	3,58	1,93	1,11	0,74
F-LD	3,00	2,13	0,80	0,27	0,26
F-HD	6,35	7,04	2,96	0,80	0,84

Table S11. Correlation matrix for chemical and ecotoxicological parameters of CLO/DGT mixtures.

Correlation Matrix

	Folsomia reproduction (% referred to the ...	Folsomia survival (% referred to the contr...	Cl- (mg/kg)	NO2- (mg/kg)	NO3- (mg/kg)	PO43- (mg/kg)	SO42- (mg/kg)	Na+ (mg/kg)	K+ (mg/kg)	NH4+ (mg/kg)	Mg2+ (mg/kg)	Ca2+ (mg/kg)	N soluble (mg/kg)	C-HCl (%)	TOC (%)	CE final 25ºC ?S/cm	CE initial 25ºC ?S/cm
Folsomia reproduction (% referred to the...	1,000	,542	-,848	,087	,082	,556	-,851	-,868	-,939	-,614	-,642	-,747	-,621	-,914	-,927	-,561	-,870
Folsomia survival (% referred to the cont...	,542	1,000	-,533	,526	-,663	,367	-,643	-,459	-,632	,019	-,290	-,865	-,009	-,468	-,445	-,170	-,772
Cl- (mg/kg)	-,848	-,533	1,000	-,362	-,137	-,721	,970	,986	,959	,369	,865	,861	,359	,890	,948	,583	,945
NO2- (mg/kg)	,087	,526	-,362	1,000	-,046	,725	-,332	-,220	-,364	,164	-,234	-,489	,191	-,230	-,215	-,353	-,430
NO3- (mg/kg)	,082	-,663	-,137	-,046	1,000	,403	,055	-,157	-,070	-,459	-,183	,350	-,407	-,230	-,246	-,480	,140
PO43- (mg/kg)	,556	,367	-,721	,725	,403	1,000	-,626	-,629	-,710	-,260	-,527	-,577	-,221	-,652	-,664	-,633	-,658
SO42- (mg/kg)	-,851	-,643	,970	-,332	,055	-,626	1,000	,968	,947	,230	,882	,934	,230	,811	,886	,403	,960
Na+ (mg/kg)	-,868	-,459	,986	-,220	-,157	-,629	,968	1,000	,943	,385	,902	,822	,378	,873	,947	,520	,910
K+ (mg/kg)	-,939	-,632	,959	-,364	-,070	-,710	,947	,943	1,000	,490	,767	,872	,487	,936	,963	,629	,967
NH4+ (mg/kg)	-,614	,019	,369	,164	-,459	-,260	,230	,385	,490	1,000	,076	,063	,998	,735	,641	,827	,337
Mg2+ (mg/kg)	-,642	-,290	,865	-,234	-,183	-,527	,882	,902	,767	,076	1,000	,716	,060	,607	,743	,244	,732
Ca2+ (mg/kg)	-,747	-,865	,861	-,489	,350	-,577	,934	,822	,872	,063	,716	1,000	,074	,693	,741	,297	,957
N soluble (mg/kg)	-,621	-,009	,359	,191	-,407	-,221	,230	,378	,487	,998	,060	,074	1,000	,732	,634	,806	,342
C-HCl (%)	-,914	-,468	,890	-,230	-,230	-,652	,811	,873	,936	,735	,607	,693	,732	1,000	,982	,821	,873
TOC (%)	-,927	-,445	,948	-,215	-,246	-,664	,886	,947	,963	,641	,743	,741	,634	,982	1,000	,735	,898
CE final 25ºC ?S/cm	-,561	-,170	,583	-,353	-,480	-,633	,403	,520	,629	,827	,244	,297	,806	,821	,735	1,000	,536
CE initial 25ºC ?S/cm	-,870	-,772	,945	-,430	,140	-,658	,960	,910	,967	,337	,732	,957	,342	,873	,898	,536	1,000

Table S12. Anions content in soils amended with DGT/CLO in Olost (OL), just after amendment application (T0) and 4 months after (T1). Treatment codes indicate the waste tested (CLO: A, B, D; DGT: C, F; C-DGT: E) and dose (HD: 80 g·kg^{-1}; LD: 20 g·kg-1). Results are expressed in mg/kg, related to soil fine fraction (<2 mm).

Treatment code	**Sampling time**	**Cl^- (mg/kg)**	**NO_2^- (mg/kg)**	**NO_3^- (mg/kg)**	**PO_4^{3-} (mg/kg)**	**SO_4^{2-} (mg/kg)**
E-OL	T0	260,6	6,7	61,5	11,2	5432,9
E-OL	T0	633,8	2,3	178,8	47,5	5224,8
E-OL	T0	675,9	3,2	167,1	48,9	4971,4
CNT-OL	T0	45,7	4,8	32,2	14,4	3820,8
CNT-OL	T0	88,9	1,9	46,4	16,8	4601,1
CNT-OL	T0	73,4	5,3	45,5	12,7	5158,8
A-OL	T0	328,5	2,8	33,7	19,9	8005,7
A-OL	T0	197,4	7,1	27,5	22,4	6466,8
A-OL	T0	187,0	9,2	36,0	17,1	6006,6
B-OL	T0	181,9	5,9	48,4	11,8	4607,3
B-OL	T0	281,8	4,8	38,9	9,4	4563,6
B-OL	T0	132,9	5,8	30,6	15,7	5003,1
C-OL	T0	405,8	5,4	26,0	13,9	6400,8
C-OL	T0	526,0	11,5	32,2	9,6	7204,9
C-OL	T0	428,1	7,1	20,6	5,1	6745,4
D-OL	T0	669,2	1,4	59,5	8,7	6764,6
D-OL	T0	324,3	1,4	45,4	12,2	6379,3
D-OL	T0	279,5	2,1	63,3	5,6	5118,9
F-OL	T0	131,0	5,1	53,1	10,5	6759,8
F-OL	T0	127,2	4,1	46,2	16,1	6653,1
F-OL	T0	137,9	5,7	48,6	20,2	6679,5
E-OL	T1	76,7	0,3	11,6	19,0	4098,4
E-OL	T1	49,7	0,0	13,3	16,8	2308,6
E-OL	T1	52,0	0,0	7,4	18,5	2922,7
CNT-OL	T1	90,5	3,8	36,5	8,5	4568,6
CNT-OL	T1	35,4	3,1	14,4	10,2	2560,4

CNT-OL	T1	68,9	3,0	34,4	11,4	5436,1
A-OL	T1	84,7	2,4	9,2	3,4	4514,2
A-OL	T1	118,6	2,9	9,6	1,1	5276,7
A-OL	T1	98,6	4,3	7,0	5,6	6381,8
B-OL	T1	96,8	1,8	41,2	12,2	4121,7
B-OL	T1	132,3	2,4	46,7	1,7	4121,4
B-OL	T1	62,2	1,4	42,2	9,0	3543,8
C-OL	T1	280,3	15,6	1399,8	15,7	7447,1
C-OL	T1	415,1	21,1	1551,6	24,8	6101,2
C-OL	T1	103,3	12,9	793,4	23,0	6260,6
D-OL	T1	80,7	0,4	18,2	58,5	5314,6
D-OL	T1	52,6	0,8	8,8	13,8	6282,7
D-OL	T1	71,5	1,0	7,1	12,1	4261,0
F-OL	T1	31,4	2,5	36,7	38,7	6596,4
F-OL	T1	98,5	3,5	47,3	55,3	4797,2
F-OL	T1	59,7	4,1	61,5	31,0	6489,7

Table S13. Cations content in soils amended with DGT/CLO in Olost (OL), just after amendment application (T0) and 4 months after (T1). Treatment codes indicate the waste tested (CLO: A, B, D; DGT: C, F; C-DGT: E) and dose (HD: 80 g·kg^{-1}; LD: 20 g·kg-1). Results are expressed in mg/kg, related to soil fine fraction (<2 mm).

Treatment code	**Sampling time**	**Na^+ (mg/kg)**	**NH_4^+ (mg/kg)**	**K^+ (mg/kg)**	**Mg_2^+ (mg/kg)**	**Ca_2^+ (mg/kg)**
E-OL	T0	160,0	26,8	126,2	98,5	4459,5
E-OL	T0	282,9	43,1	218,3	127,7	4300,5
E-OL	T0	343,6	50,8	208,9	173,5	3631,2
CNT-OL	T0	30,6	12,8	36,8	61,8	3004,4
CNT-OL	T0	52,9	13,9	65,7	94,1	3631,3
CNT-OL	T0	52,7	12,8	65,2	119,8	4133,7
A-OL	T0	256,5	40,5	133,0	173,3	8363,1
A-OL	T0	161,3	22,1	80,1	113,0	5840,5
A-OL	T0	154,7	26,7	80,2	108,7	5207,5
B-OL	T0	128,2	16,3	79,5	93,7	3746,3
B-OL	T0	158,9	20,6	90,1	99,0	3772,9
B-OL	T0	97,7	18,0	62,0	66,1	4320,3
C-OL	T0	181,9	201,6	157,3	127,2	5350,4
C-OL	T0	222,3	281,7	192,3	144,0	6264,6
C-OL	T0	187,1	204,9	159,7	128,4	5802,0
D-OL	T0	290,2	26,6	147,2	172,7	6364,9
D-OL	T0	230,5	17,8	105,9	113,6	5857,3
D-OL	T0	193,2	17,4	88,3	97,0	4237,0
F-OL	T0	104,4	68,3	86,4	113,8	6057,6
F-OL	T0	102,1	62,8	81,8	111,8	5931,0
F-OL	T0	108,4	72,2	87,5	117,0	5881,5
E-OL	T1	80,7	7,5	72,8	75,3	3049,1
E-OL	T1	56,7	7,4	56,3	57,8	1909,8
E-OL	T1	51,8	4,8	47,8	42,1	2378,8
CNT-OL	T1	76,3	10,6	59,6	96,7	3602,1
CNT-OL	T1	25,9	5,4	28,5	55,4	2094,4

CNT-OL	T1	71,9	5,4	58,5	96,2	4461,9
A-OL	T1	87,9	10,1	65,4	124,4	4085,9
A-OL	T1	123,8	12,3	75,7	120,5	4664,2
A-OL	T1	112,2	7,6	64,7	114,9	5608,7
B-OL	T1	92,5	11,8	69,1	110,4	3501,8
B-OL	T1	123,0	9,9	53,9	60,8	2523,1
B-OL	T1	78,5	11,5	53,9	74,8	2787,3
C-OL	T1	181,7	23,1	116,8	190,7	8003,5
C-OL	T1	197,1	24,1	131,1	195,1	6022,3
C-OL	T1	83,6	12,8	62,2	109,5	6093,4
D-OL	T1	95,0	9,0	67,0	88,5	4739,6
D-OL	T1	76,1	7,4	47,2	58,9	5722,8
D-OL	T1	71,9	10,7	70,9	86,0	3847,8
F-OL	T1	65,6	7,9	46,8	112,6	6059,3
F-OL	T1	60,1	8,1	44,3	127,0	4323,6
F-OL	T1	60,3	7,2	45,9	115,2	5803,7

Table S14. Floristic inventory of OL plots during the first summer (six months after soil restoration) and abundance estimation (1=testimonial, 2=present, 3=abundant, 4=very abundant, 5=dominant).

Species	**CNT-OL**	**A-OL**	**B-OL**	**C-OL**	**D-OL**	**E-OL**	**F-OL**
Anthemis cotula L.	1				1	1	1
Avena barbata	3	2	2	4	2	2	3
Bromus madritensis L.	1	1	1	2	1	1	1
Centaurea aspera L. ssp. aspera		1					
Chenopodium album	1	1		2	1	1	1
Cirsium marianum			1		1		
Conyza canadensis					1		
Cynodon dactylon					1		
Daucus carota					1		
Dactylis glomerata			1				
Diplotaxis erucoides				1			1
Echium vulgare						1	
Erigeon sp.					1		1
Festuca arundinacea					1	1	
Lactuca serriola	1			1	1	1	1
Lolium multiflorum	2	2	3	2	3	2	2
Lolium perenne	1	1	1	1	1	1	1
Lolium rigidum	2	4	4	4	4	4	3
Malva sylvestris L.			1			1	
Medicago sativa	1					1	
Medicago truncatula Gaertn	1	1			1	1	1
Melilotus officinalis	2		1		1	1	1
Papaver rhoeas	3		1	1	1	2	3
Phalaris brachystachis Link		1	1				

Table S14bis. Floristic inventory of OL plots during the first summer (six months after soil restoration) and abundance estimation (1=testimonial, 2=present, 3=abundant, 4=very abundant, 5=dominant).

Species	**CNT-OL**	**A-OL**	**B-OL**	**C-OL**	**D-OL**	**F-OL**	**E-OL**
Picris hieracioides L.					1		
Polygonum aviculare L.	1	1		2	1		
Rumex crispus L.	1	1	1		1		1
Sonchus arvensis			1		1		1
Triticum sp.	1		1	1		1	1
Verbena officinalis L.			1		1	1	
Vicia cracca L.	1	1					

Table S15. Floristic inventory of OL plots during the first autumn (ten months after soil restoration) and abundance estimation (1=testimonial, 2=present, 3=abundant, 4=very abundant, 5=dominant).

Species	CNT-OL	A-OL	B-OL	C-OL	D-OL	E-OL	F-OL
Amaranthus retroflexus		2	1	4	2	2	2
Chenopodium album	4	2	2	5	2	3	3
Conyza canadensis	2	1					
Convolvulus arvensis				1	1		
Cynodon dactylon	1	2	1	2	3	2	2
Diplotaxis erucoides	2			2	1	1	2
Ecballium elaterium	1						1
Echinochloa crus-galli		1			1		
Echium vulgare	1		1	1		2	1
Lactuca serriola				1		1	
Lolium sp.	3	1	2	1	2		2
Malva sylvestris L.	1		2	1	1	1	1
Medicago sativa	1		1		2		1
Melilotus officinalis	2	3	1	1	1	2	2
Onobrychis sativa	1						
Panicum miliaceum			1				
Plantago lanceolata	2	2	2		2	2	1
Polygonum aviculare L.		1			1		
Portulaca oleracea	1	2	1	2	2	1	1
Sanguisorba minor					1		
Setaria viridis	4	2	3	2	3	2	3
Solanum nigrum							1
Sonchus arvensis	3	1	2	2	1	3	2
Veronica sp.	1		1			1	
Vicia cracca L.					1		

Table S16. Floristic inventory of TE plots during the first summer (six months after soil restoration) and abundance estimation (1=testimonial, 2=present, 3=abundant, 4=very abundant, 5=dominant).

Species	CNT-TE	C-TE	E-TE
Anagallis arvensis		1	1
Avena barbata	1		
Brachypodium phoenicoides	1		
Bromus madritensis		1	1
Bromus sterilis		2	1
Carduus nigrescens		2	2
Cerastium glomeratum		1	
Chenopodium album	1	3	3
Chenopodium opulifolium	1	2	2
Conyza bonariensis	2	1	2
Coriaria myrtifolia	1		
Crepis vesicaria subsp. taraxacifolia	2	2	1
Dactylis glomerata	2	5	5
Diplotaxis erucoides	1	2	2
Echium vulgare	2	2	2
Erucastrum nasturtiifolium (E. obtusangulum)		1	
Festuca arundinàcia	2	1	1
Foeniculum vulgare	1		1
Fumaria capreolata		1	
Galactites tomentosa	2	2	2
Galium aparine subsp. aparine	1		
Geranium rotundifolium		1	
Inula viscosa (Dytrichia viscosa)	2	2	2
Lamium amplexicaule subsp. amplexicaule		1	
Lolium perenne			2
Lotus corniculatus	1		
Malva sylvestris	1	2	2
Matricaria recutita		1	
Medicago minima	1		
Medicago sativa	3	1	1

Table S16bis. Floristic inventory of dominant plants on TE plots during the first summer (six months after soil restoration) and abundance estimation (1=testimonial, 2=present, 3=abundant, 4=very abundant, 5=dominant).

Species	CNT-TE	C-TE	E-TE
Melilotus sulcatus	2		1
Mentha pulegium	1	1	
Moricandia moricandioides subsp. moricandioides	1		1
Myosotis arvensis subsp. arvensis		1	1
Onobrychis viciifolia	3	2	2
Oryzopsis miliacea		1	
Papaver roheas	2	1	2
Plantago lanceolata	1	1	
Polypogon monspeliensis			1
Ranunculus bulbosus subsp. aleae	1	1	1
Rubus ulmifolius	2		
Rumex cristatus			1
Sanguisorba minor	1		
Scholimus hispanicus		1	1
Solanum nigrum		1	1
Sonchus asper	1	2	2
Taraxacum officinale	1		
Triticum vulgare		1	
Veronica arvensis	1	2	1
Vicia cracca subsp. tenuifolia	3	1	1
Xanthium spinosum		1	

Table S17. Floristic inventory of dominant plants on LM plots during the first summer (six months after soil restoration) and autumn (ten months after soil restoration), and abundance estimation (1=testimonial, 2=present, 3=abundant, 4=very abundant, 5=dominant).

Species	**Abundance**			
	SUMMER		**AUTUMN**	
	CNT-LM	**L-LM**	**CNT-LM**	**L-LM**
Chenopodium album	4	2	2	5
Dittrichia viscosa			2	
Daucus carota	1			
Echinochloa crus-galli	1		1	
Erucastrum nasturtiifolium	3	2		
Festuca sp.	2	4		
Hordeum vulgare		1		
Lolium perenne	2	4	2	4
Medicago sativa	2	5	2	5
Onobrychis sativa	1	3		
Oryzopsis miliacea	1			
Paspalum notatum	2		2	
Picris hieracioides		1		
Sonchus sp.		1		