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A new technology to restore soil fertility: reconstitution

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SUMMARY. – Soil degradation is characterized by the reduction of soil thickness and fertility. Reconstitution technique was used to reclaim the degraded soil covering a closed landfill and to restore the fertility of farm soils in Northern Italy (Piacenza province, Emilia-Romagna region). Reconstitution applied chemical and mechanical actions to degraded soils and/or alluvial sediments mixed with waste from different productive processes. The aim of this study was to describe how reconstitution changed the physicochemical properties of the original soils used in the mixture. The results show that reconstitution produced soils with improved physical properties; on average, in reconstituted soils bulk density was 45% and particle density was 10% lower than original soils. The same was observed for the chemical properties; on average, in reconstituted soils pH was 5% lower than original ones, whereas organic C was 82% and N was 59% higher.

INTRODUCTION. – Healthy soils have both inherent and dynamic qualities able to promote and sustain agricultural productivity with minimal environmental degradation for future use. A soil with poor quality might not have some or all the attributes required for a good agricultural production and might be prone to environmental degradation (REYNOLDS *et al.*, 2007). Erosion, compaction, sealing, loss or change in the aggregates structure, reduction of water holding capacity and organic matter cause environmental effects such as diminishing physical and chemical fertility and decline of biodiversity.

The attention to soil degradation and desertification is frequently based on studying the processes involved in soil quality attributes and seeking actions for soil improvement and protection. For soil reconstruction interventions Technosols are used (FAO and ITPS, 2015), a new group of soils strongly influenced by technical human activity (MACÍA *et al.*, 2014). They are defined as soils "containing significant amounts

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of artifacts and whose properties and pedogenesis are dominated by their technical origin" (IUSS, 2006). In the current valid version of WRB (World Reference Base of Soil Resources) (IUSS, 2015) such soils are described as characterized by the presence of diagnostic materials (artifacts and technic hard materials) that significantly influence soil-forming processes or are indicative of them. Artifacts are defined as substances that are created or substantially modified by humans as part of an industrial or artisanal manufacturing process. Technic hard materials are defined as consolidated materials resulting from an industrial process which physicochemical properties are substantially different from those of natural materials. Depending on the type of artifacts, three qualifiers are provided. The Urbic qualifier stands for rubble and refuse from human settlements, the Spolic qualifier for industrial waste (mine spoil, dredging, slag, ash, rubble, etc.) and the Garbic qualifier for organic waste (SCHAD, 2018).

In the development of soil reclamation the following aspects have to be considered: the design of a specific Technosol using adequate matrices (BUONDONNO *et al.*, 2013; CAPRA *et al.*, 2011, 2015); the designed soil must be consistent with the distinctive environment in which the soil itself will be built; and the matrices must be allowed by law, must contain plant nutrients and must have pedogenic potential (GRILLI *et al.*, 2011), i.e. characterized by a combination of attributes that reflect common results of the processes of soil formation (SCHAD, 2018).

In this paper, a plot experiment using a reconstituted soil is presented with the aim to describe a technology to counter soil degradation. Reconstitution is a patented technique that produces Technosols called reconstituted soils. By reconstitution chemical and mechanical treatments are applied to a mixture of degraded soils, alluvial sediments and waste from different production processes (e.g. paper mill sludge); these treatments affect the physicochemical properties of degraded soils/alluvial sediments. Reconstituted soils analyzed in this paper were produced using a mixture of degraded soil/alluvial sediment and paper mill sludge.

The experiment involved a plot comparison among natural soils affected by degradation and alluvial sediments and the reconstituted soils. The specific aims were to evaluate the effect of the reconstitution technology on soil properties under agricultural use: i) on degraded soils and alluvial sediments and ii) using different types of paper mill sludge.

TABLE 1. – *Physicochemical analysis and description of the sludges.*

Sludge	BD kg m^{-3}	PD kg m^{-3}	pH	Organic C %	Total N %	C/N	Type of sludge
a	570	1310	8.2	37.0	0.29	128	mechanical separation of waste fibers and depuration of production water
b1	730	1700	8.3	16.8	0.39	43	primary and secondary treatment
b2	1140	1880	8.4	15.6	0.62	25	primary and secondary treatment
b3	1190	1300	8.2	19.5	0.49	40	primary and secondary treatment
c	770	1720	8.3	21.3	0.68	31	cleaning of the dough and suspended biomass depuration
d	450	1660	8.1	16.8	0.24	70	sedimentation and oxidation of de-inking recycling paper wastewater

BD, bulk density; PD, particle density.

MATERIALS AND METHODS. – *The reconstitution technology*. – The reconstituted soils were produced by a technology developed to restore the fertility of degraded soils by the m.c.m. Ecosistemi research laboratory (Gariga di Podenzano, Piacenza province, Emilia-Romagna region) and protected by two patents. The reconstituted soil was the result of chemical and mechanical treatments applied to a mixture of degraded soil and waste from different production processes, such as sludge from paper industry and cellulose transformation processes, washing sludge of inert materials and water treatment sediments for drinking water supplies. The chosen wastes were chemically characterized and thereafter added to the degraded soil in a suitable amount on the basis of their chemical analysis – the potential toxic heavy metal concentration in all the sludges was analyzed, and the sludge amount in the mixture was calibrated so to obtain a heavy metal content in reconstituted soils below the critical limits imposed by regulation concerning the agronomic use of the soil (Italian Government Ordinance, March 1, 2019, No. 46). The mixture was then crushed, producing a breakdown of the lignocellulosic components, and the organic fraction was incorporated into the mineral particles of the soil. Then a mechanical compression made the reconstituted soil aggregates. This treatment allowed the organic components, represented by hemicellulose, cellulose, lignin and soluble fractions of organic carbon, to be included in the soil mineral fraction by means of a defined stable soil aggregate (Manfredi, 2016). The produced Technosol had high fertility in comparison with the degraded soil used in the mixture and showed different properties from the materials used (Manfredi *et al.*, 2015, 2019a). The reconstituted soils described in the presented test were produced by mixing natural soils affected by degradation and alluvial sediments with plant water treatment sludge and paper industry sludge resulting from pulp and papermaking.

Paper industry sludges used were (Table 1):

a) sludge from mechanical separation of waste fibers and depuration of water;
b) sludge from primary and secondary treatment of settling, clarification and purification of wastewater, which contained calcium carbonate (b1, b2, b3 indicate 3 different paper industries);
c) sludge from suspended solids thickening in wastewater, resulting from the cleaning of the dough and the suspended biomass depuration;
d) sludge from sedimentation and oxidation of de-inking recycling paper wastewater.

Experimental plots. – Twenty-four experimental plots (3 m × 5 m) were set up at a farm in Northern Italy (Gossolengo, Piacenza province, Emilia-Romagna region). These were divided into a group of 10 plots with degraded soils and alluvial sediments (called original soils) and 14 reconstituted soil plots. The 10 plots with original soils were further subdivided: 4 plots with alluvial sediments and 6 plots with degraded soils. The 14 reconstituted soil plots were subdivided on the basis of the materials used into the mixture (alluvial sediments + sludges, degraded soil + sludges). The alluvial sediments (alluvial sand, mixed inert material wastes from washing activities of natural aggregates, and 2 alluvial clayey sediments) were sampled in Piacenza. The degraded soils were from the cover soil of a closed landfill (Borgotrebbia, Piacenza) and from a farm in Gossolengo (Piacenza). These original soils, taken in a suitable amount from the source (about 50 kg each), were moved to the reconstitution site. An aliquot (about 30 kg) was used to prepare the 10 soil plots, while reconstitution was applied on the remaining soil.

The sludges came from 6 Italian paper industries and differed in bulk and particle density, pH, organic C and total N contents (Table 1).

The plots were divided into two groups, each named with letters and numbers. The letter O represents original soil plots; the letter R reconstituted soil plots. The number represents the original soil both in O and in R plots (Fig. 1). The plots 1-2-3-4 O compared alluvial sediments with the same soils once reconstituted (1-2-3-4 R). The plots 5-6-7-8-9 O compared five degraded soil with the same soils once reconstituted (5-6-7-8-9 R). The plots 10 O - 10 R 1 - 10 R 2 - 10 R 3 - 10 R 4 - 10 R 5 - compared a farm degraded soil (10 O) with the same soil mixed with 5 different sludges and reconstituted. All the reconstituted soil plots were made according to a ratio (w/w) of 50% original soil + 50% sludge. Considering the chemical characterization of the sludge and original soil, the mixture was 50% (w/w) in order to have the same input from original soil and matrices in all the plots. For plots 1-2-3-4-5-6-7-8-9 R reconstitution was carried out using the same sludge types a and b1 (25% a + 25% b1); in this case the effect of reconstitution on different original soils was tested. For plots 10 R reconstitution was performed using different sludges (R 1 c, R 2 b3, R 3 b2, R 4 d, R 5 a); in this case the effects of different sludges were tested.

Original soil plots		Sludges		Reconstituted soil plots
alluvial sand 1 O	+	sludge a + sludge b1	→	1 R
inert material from washing activities 2 O	+	sludge a + sludge b1	→	2 R
alluvial clayey sediments 3 - 4 O	+	sludge a + sludge b1	→	3 - 4 R
closed landfill soil 5 - 6- 7- 8 - 9 O	+	sludge a + sludge b1	→	5 - 6- 7- 8 - 9 R
farm soil 10 O	+	sludge c	→	10 R 1
farm soil 10 O	+	sludge b3	→	10 R 2
farm soil 10 O	+	sludge b2	→	10 R 3
farm soil 10 O	+	sludge d	→	10 R 4
farm soil 10 O	+	sludge a	→	10 R 5

Fig. 1. Description of plots.

TABLE 2. – *Particle size distribution and texture class of the plots.*

Plot	**Sand** %	**Silt** %	**Clay** %	**Texture class**
1 O	86.8	13.2	0.0	loamy sand
1 R	86.3	8.5	5.2	loamy sand
2 O	42.5	49.9	7.6	loam
2 R	61.6	33.8	4.6	sandy loam*
3 O	6.8	38.5	54.7	clay
3 R	32.3	28.3	39.4	clay loam*
4 O	4.6	36.5	58.9	clay
4 R	26.6	29.1	44.3	clay
5 O	19.3	66.3	14.4	silty loam
5 R	16.6	73.4	10.0	silty loam
6 O	22.3	58.5	19.2	silty loam
6 R	22.5	65.0	12.5	silty loam
7 O	22.3	62.9	14.8	silty loam
7 R	15.2	70.7	14.1	silty loam
8 O	27.8	56.2	16.0	silty loam
8 R	23.1	65.1	11.8	silty laom
9 O	23.4	55.3	21.3	silty loam
9 R	17.7	72.6	9.7	silty loam
10 O	46.8	34.4	18.8	loam
10 R 1	35.7	38.2	26.1	loam
10 R 2	30.2	48.2	21.6	loam
10 R 3	19.9	56.4	23.7	silty loam*
10 R 4	54.2	32.5	13.3	sandy loam*
10 R 5	36.1	37.7	26.2	loam

The same number represents the same soil (O, original soil plots; R, reconstituted soil plots). * indicates a change in the texture class in reconstituted plot.

All plots were set up at the same time and located in the same area. Thereafter, no treatment was applied, and soils were neither tilled nor cultivated. Samplings on plots were carried out in the period 2013-2016, the first about one month following the set-up and then every six months.

Soil sampling and analysis. – Every soil sample (0-20 cm) for physical and chemical analysis was made of three sub-samples (350 g each), and was collected randomly from the plot (Tables 2, 3 and 4).

Physicochemical analyses were performed on air-dried (< 2 mm) soil according to official Italian procedures. Physical analysis (texture, bulk density and particle density) followed MIPAAFT (1997) protocols; chemical analysis (pH, organic C and total N) followed MIPAAFT (2000) procedures. Sand (2.0-0.02 mm), silt (0.02-0.002 mm) and clay (< 0.002 mm) fractions were separated by the hydrometer method. Bulk density was calculated weighing a known volume of 105°C-dried soil. Particle density was measured using a pycnometer. pH was measured on 1:2.5 soil/water mixtures. Organic carbon was oxidized with potassium dichromate and titrated (WALKLEY and BLACK, 1934). Total nitrogen was measured by the Kjeldahl procedure. C/N was calculated. Porosity (%) was calculated using bulk density and particle density:

$$\text{Porosity} = \left(1 - \frac{\text{bulk density}}{\text{particle density}}\right) \times 100$$

The soil structural "stability index" (SI) (%) (Table 5) was calculated according to the following equation (PIERI, 1992):

$$\text{SI} = \frac{1.72 \times \text{OC}}{(\text{Clay+Silt})} \times 100$$

where OC is the organic C content (%), and Clay + Silt (%) is the combined soil clay and silt content.

Statistical analysis. – Soil physical (bulk and particle density, porosity) and chemical data (pH, organic C, total N and C/N) were statistically evaluated after having checked normality and homoscedasticity. To test the effect of reconstitution on different original soils, t-test for paired samples was performed considering the average of the physicochemical data of plots 1-2-3-4-5-6-7-8-9 O/R. To test the effects of different sludges used to reconstitute the same degraded soil, Analysis of Variance (ANOVA) was performed on the chemical data (pH, organic C, total N and C/N) of 10 O/10 R 1-2-3-4-5 plots. Moreover, Least Significant Difference (LSD) was used to evaluate which sludge provided the best chemical effects.

The statistical software IBM SPSS version 21 was used.

RESULTS. – *Changes in soil physical properties.* – Reconstitution only affected soil texture in 4 cases (plots 2 R, 3 R, 10 R 3-4), whereas in the remaining reconstituted plots the contents of sand, silt and clay

TABLE 3. – *Physicochemical analysis (mean ± SD) and -test for paired samples of plots 1-2-3-4-5-6-7-8-9 O/R*.

Plot	BD**	PD**	Porosity**	pH**	Organic C**	Total N**	C/N*
	kg m^{-3}	kg m^{-3}	%		%	%	
1 O	1484 ± 95	2689 ± 150	45 ± 9	8.3 ± 0.22	0.09 ± 0.01	0.03 ± 0.02	3 ± 1
1 R	707 ± 43	2039 ± 98	65 ± 6	7.9 ± 0.08	6.28 ± 1.43	0.28 ± 0.12	23 ± 8
2 O	1257 ± 87	2341 ± 102	47 ± 4	8.3 ± 0.17	0.15 ± 0.03	0.05 ± 0.01	3 ± 1
2 R	688 ± 65	2066 ± 76	67 ± 12	7.9 ± 0.02	8.16 ± 0.23	0.20 ± 0.02	40 ± 3
3 O	1270 ± 89	2232 ± 96	44 ± 6	7.7 ± 0.03	0.32 ± 0.41	0.07 ± 0.01	4 ± 1
3 R	818 ± 25	1737 ± 104	53 ± 5	7.7 ± 0.24	7.40 ± 1.69	0.21 ± 0.04	36 ± 9
4 O	1378 ± 99	2077 ± 178	34 ± 13	8.1 ± 0.10	0.23 ± 0.03	0.06 ± 0.01	4 ± 1
4 R	637 ± 37	1906 ± 74	67 ± 11	7.8± 0.15	7.91 ± 0.44	0.30 ± 0.02	26 ± 5
5 O	1041 ± 78	2143 ± 86	51 ± 7	8.0 ± 0.14	3.07 ± 0.63	0.33 ± 0.05	9 ± 2
5 R	551 ± 47	1894 ± 92	71 ± 9	7.8 ± 0.18	7.51 ± 0.03	0.68 ± 0.02	11± 2
6 O	1491 ± 66	2196 ± 121	32 ± 4	8.3 ± 0.45	1.83 ± 0.29	0.23 ± 0.07	8 ± 1
6 R	705 ± 30	2043 ± 80	65 ± 14	7.8 ± 0.12	9.35 ± 0.36	0.68 ± 0.06	14 ± 2
7 O	1319 ± 71	2288 ± 96	42 ± 5	8.1 ± 0.28	1.90 ± 0.24	0.22 ± 0.04	9 ± 1
7 R	403 ± 22	1982 ± 162	80 ± 9	7.8 ± 0.13	8.53 ± 0.64	0.71 ± 0.07	12 ± 6
8 O	1209 ± 55	2296 ± 63	47 ± 9	8.0 ± 0.27	2.78 ± 0.80	0.27 ± 0.09	10 ± 2
8 R	644 ± 29	2063 ± 88	69 ± 11	7.8 ± 0.22	5.07 ± 0.50	0.48 ± 0.06	11 ± 4
9 O	1349 ± 95	2272 ± 132	41 ± 5	8.0 ± 0.19	2.87 ± 1.00	0.35 ± 0.07	8 ± 1
9 R	903 ± 36	1988 ± 99	55 ± 6	7.9 ± 0.19	6.49 ± 0.38	0.61 ± 0.02	11 ± 2

BD, bulk density; PD, particle density. The same number represents the same soil (O, original soil plots; R, reconstituted soil plots). [a]Means within a column and plot type are significantly different at P <0.05 if followed by *, and at P <0.01 if followed by **.

TABLE 4. – *Physicochemical analysis (mean ± SD) of plots 10 O/R 1-2-3-4-5; LSD test on chemical analysis*.

Plot	BD	PD	Porosity	pH	Organic C	Total N	C/N
	kg m^{-3}	kg m^{-3}	%		%	%	
10 O	1233 ± 29	2290 ± 73	45 ± 6	8.26 ± 0.28 ^{a}	0.83 ± 0.22 ^{d}	0.13 ± 0.04 ^{c}	7 ± 1 ^{d}
10 R 1	767 ± 18	2259 ± 85	67 ± 9	7.23 ± 0.13 ^{c}	4.07 ± 0.31 ^{c}	0.44 ± 0.07 ^{a}	9 ± 2 ^{d}
10 R 2	781 ± 23	1946 ± 65	60 ± 6	7.75 ± 0.27 ^{b}	6.17 ± 0.78 ^{b}	0.30 ± 0.09 ^{ab}	22 ± 6 ^{bcd}
10 R 3	768 ± 36	2346 ± 69	68 ± 11	7.80 ± 0.22 ^{ab}	4.85 ± 0.60 ^{c}	0.24 ± 0.06 ^{bc}	20 ± 6 ^{cd}
10 R 4	734 ± 29	2018 ± 59	64 ± 9	7.89 ± 0.19 ^{ab}	11.23 ± 1.20 ^{a}	0.21 ± 0.07 ^{bc}	53 ± 23 ^{a}
10 R 5	569 ± 26	2057 ± 79	73 ± 12	7.97 ± 0.18 ^{ab}	12.34 ± 0.12 ^{a}	0.27 ± 0.02 ^{bc}	46 ± 5 ^{abc}

BD, bulk density; PD, particle density. The same number represents the same soil (O, degraded soil plots; R, reconstituted soil plots). Different letters indicate statistically significant difference (P ≤ 0.01).

changed in comparison with the original soil, but texture class remained unchanged (Table 2). In plot 2 the texture class was loam in plot O, and sandy loam in R. In plot 3 the texture class was clay in plot O, and clay loam in R. In plot 10 the texture class was loam in plot O, silty loam in R 3 and sandy loam in R4.

The bulk and particle densities were always lower in reconstituted than in original soils (Tables 3 and 4). The mean bulk density reduction was 48% in 1-2-3-4-5-6-7-8-9 R plots and 41% in 10 R plots; the data were statistically different at $P \leq 0.01$. The mean particle density reduction was 13% in 1-2-3-4-5-6-7-8-9 R plots and 7% in 10 R, and the data were statistically different at $P \leq 0.01$. The porosity was 35% higher in 1-2-3-4-5-6-7-8-9 R plots and 32% in 10 R plots compared to the values of the original soil plots; the data were statistically different at $P \leq 0.01$.

Changes in soil chemical properties. – Soil pH decreased due to reconstitution: in comparison with the original soils, mean pH reduction was 4% in 1-2-3-4-5-6-7-8-9 R plots and 6% in 10 R plots (values were statistically different at $P \leq 0.01$). Organic C contents were statistically different at $P \leq 0.01$ as well; on average they were always much higher in reconstituted than in original soils. In comparison with original soils the mean organic C increase was 79% in 1-2-3-4-5-6-7-8-9 R plots and 86% in 10 R plots. Similarly, total N contents – statistically different at $P \leq 0.01$ – were higher in reconstituted than in original soils. In comparison with original soils, the mean total N increase was 65% in 1-2-3-4-5-6-7-8-9 R plots, and 53% in 10 R plots. Consequently, the C/N ratio was higher in reconstituted than in original soils; in this case data were statistically different at $P \leq 0.05$ in 1-2-3-4-5-6-7-8-9 plots and $P \leq 0.01$ in 10 R plots. In comparison with original soils, the mean C/N increase was 51% in 1-2-3-4-5-6-7-8-9 R plots and 69% in 10 R plots.

Considering pH, organic C, total N and C/N data of plots 10 O/R, LSD test was used to evaluate the effects of the sludges used (Table 4). All chemical data were statistically different at $P \leq 0.01$. pH decreased in all reconstituted soils, mostly in the 10 R 1 plot, while 10 R 3-4-5 plots were statistically similar to the degraded one. Organic C increased in all reconstituted soils, to a higher extent in 10 R 4-5 plots compared to 10 R 1-3. Total N increased in all reconstituted plots, with higher increases in 10 R 1-2 than in 10 R 3-4-5, that were similar each other. The C/N increased in all reconstituted plots and increased more in 10 R 4-5 plots, while 10 O and 10 R 1 were similar to each other.

TABLE 5. – *Soil structural stability index (SI).*

Plot	SI %	Plot	SI
1 O	*1*	7 O	*4*
1 R	*79*	7 R	*17*
2 O	*< 1*	8 O	*7*
2 R	*37*	8 R	*11*
3 O	*< 1*	9 O	*6*
3 R	*19*	9 R	*14*
4 O	*< 1*	10 O	*3*
4 R	*18*	10 R 1	*11*
5 O	*6*	10 R 2	*16*
5 R	*15*	10 R 3	*10*
6 O	*4*	10 R 4	*40*
6 R	*21*	10 R 5	*33*

SI, soil structural stability index was calculated using the organic C, silt and clay values of the plot. The same number represents the same soil (O, original soil plots; R, reconstituted soil plots). SI color index description:

SI ≤ 5	5 < SI ≤ 7	7 < SI ≤ 9	SI > 9

The soil structural stability index (SI) was calculated using organic C, silt and clay (Table 5). SI ≤ 5 indicates structurally degraded soil due to extensive loss of organic C; 5 < SI ≤ 7 indicates a high risk of structural degradation due to insufficient organic C; 7 < SI ≤ 9 indicates a low risk of soil structural degradation; and SI > 9 indicates enough soil organic C to maintain structural stability. Note that as SI is based on organic C content and texture, it does not relate directly to the soil porosity structure, but to the resilience of the structure (REYNOLDS *et al.*, 2009). In plots 1-2-3-4-6-7-10 O, SI ≤ 5% suggested that soils were structurally degraded due to extensive loss of organic C. In plots 5-8-9 O, 5% < SI ≤ 7% indicated a high risk of structural degradation due to insufficient organic C. In all reconstituted soil plots SI > 9% showed that soils had enough organic C to maintain structural stability.

DISCUSSION. – The results show the effects of the use of paper mill sludge in reconstitution for reclaiming degraded soil/alluvial sediment. MANFREDI *et al.* (2012, 2019b) also described the effect of reconstitution – using a mixture of degraded soil and paper sludge – on soil fertility by agronomic tests on maize and tomato. MANFREDI *et al.* (2019a) used Land Capability Classification and Fertility Capability Classification to assess the changes in fertility caused by reconstitution.

All the sludges – having a high organic matter content due to celluloses, hemicelluloses, lignin and containing minerals (calcium carbonate and kaolin) – mixed with alluvial sand and clay sediments, or inert material from washing activity or degraded soil changed bulk and particle densities, pH, organic C, total N and the stability index.

The decrease in reconstituted soil bulk and particle density was due to the increase in organic C and to the better particle aggregation resulting from mechanical actions. Increased soil porosity, combined with the decreasing bulk density, improved the exchange between gas, liquid and solid soil phases; this was typical of a fertile soil with good amount of humus where the root system was able to develop well. However, bulk density values below 900 kg m^{-3} can potentially result in yield loss due to inadequate plant anchoring, reduced plant-available water and unsaturated water flow, and dissolved nutrients (REYNOLDS *et al.*, 2008, 2009; MUELLER *et al.*, 2008). Porosity values higher than 65-66% can be considered quite high since they can indicate relatively low water retention. However, in reconstituted soils the relation between porosity and water holding capacity cannot be considered true. As a matter of fact, in order to relate porosity and water holding capacity, the type of porosity to be considered must be specified. Indeed, the real soil porosity, the size distribution of porosity and the porosity calculated by bulk and particle densities are very different from each other. RAIMO and NAPOLITANO (2002) demonstrated that the size distribution of soil porosity was largely influenced by the presence of organic matter, which had the ability to produce relatively stable aggregates among the particles. For this reason, the real soil porosity may be very different from particle size distribution determined by laboratory measurements of soil samples in which this aggregation might have been partially destroyed. Soil organic matter acts as a bonding material in soil structure formation (OADES, 1984); it forms complexes with primary mineral particles and secondary structural units. In this way, inter-aggregate pores were formed, and the result was a general reduction in bulk density (REYNOLDS *et al.*, 2007; MUNKHOLM, 2001). By calculating the structural stability index, reconstituted soils demonstrated they had sufficient organic C to be resilient. This is probably because, by destroying the structural arrangement of the mineral particles, by changing the organic matter protection and by adding organic matter reconstitution caused the organic matter to redistribute onto mineral surfaces, thus forming neo-aggregates in which clay and high organic C played an important role. In contrast, original soils had a high risk of structural degradation or were structurally degraded due to an extensive loss of organic C (MANFREDI *et al.*, 2016).

High soil organic C in reconstituted soils was due to the sludges used, but this high content would not be obtained by simply mixing or distributing soil amendments. As a matter of fact, some amendment effects may be not effective in the long-term (MACÍAS, 2004, 2011) making successive applications necessary (PÉREZ-DE-MORA *et al.*, 2011) which increases the cost of the technology. The reconstituted soil C/N value indicates a stable equilibrium between mineralization and humification, allowing the preservation of stable forms of organic C. 2 R, 3 R, 10 R 4-5 had C/N values > 30. These soils will have a slow mineralization but the presence of lignin and cellulose from sludge will allow the creation of stable organic matter. In contrast, degraded soil C/N ratio indicated mineralization and N loss by leaching. pH decreased in reconstituted soils, remaining moderately alkaline.

The t-test shows significant differences between reconstituted soils and original ones. Analysis of Variance shows that different sludges acted in different ways. Considering the degraded soil 10 O properties (0.83% organic C, 0.13% total N and C/N ratio equal to 7) in comparison with those of 10 R 1-2-3-4-5, supported by ANOVA and LSD outputs, some considerations can be made about the effects of sludges. All the sludges improved the properties of degraded soil in different ways. In the reconstituted soils derived from primary and secondary treatments of settling, clarification and purification of wastewater (10 R 2-3-5) sludge increased organic C to 6.17%, total N to 0.30% and C/N to 22 in the 10 R 2 plot; organic C content to 4.85%, total N to 0.24% and C/N 20 in 10 R 3; and organic C to 12.34%, total N to 0.27% and C/N to 46 in 10 R 5. In reconstituted soil made from sludge from suspended solids thickening in wastewater resulting from the cleaning of dough and suspended biomass depuration (10 R 1) sludge increased organic C to 4.07%, total N to 0.44% and C/N to 9. In the reconstituted plot originated from sludge from sedimentation and oxidation of de-inking recycling paper wastewater (10 R 4), sludge increased organic C to 11.23%, total N to 0.21% and C/N to 53.

CONCLUSIONS. – Reconstitution is a technology that works actively to counteract soil degradation and desertification through soil fertility recovery. In the study presented, the use of paper mill sludge demonstrated it had positive effects on the physicochemical properties of reconstituted soils. The use of degraded soil/alluvial sediments mixed with waste from production processes is a green and efficient way to restore degraded and desertified soils. Indeed, soil is a limited, declining resource and more soils are increasingly affected by degradation, while wastes are produced in massive quantities and destined to the dump or incineration. The recycle of waste (Directive 2008/98/EC) – circular economy – is a very important goal for the EU; in this context, considering the materials used in reconstitution, reconstitution technology can provide new opportunities for circular economy. Further work is required to test the recycling of different matrices. Nowadays, reconstitution is applied to a mixture of dredge sediments (which are considered waste by Italian legislation), degraded soil and paper mill sludge, and the reconstituted soil is studied by a lysimeter and a pot test.

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