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The reconstitution pedotechnique: Applications

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A B S T R A C T

The reconstitution pedotechnique is a process based on the treatment of organic and nonorganic matrices for restoring ecosystem and agroforestry functions of soils and for producing specific Technosols. The technology applies a conceptual model based on the production of new soil aggregates with targeted environmental and soil characteristics generated via a chemical–mechanical process that entails reusing residues of a specific origin. The activity is consistent with the principles of circular economy, applying restoration ecology and valorization of compatible waste and saving nonrenewable resources. The applications of reconstitution technology are aimed at different kinds of interventions; this paper presents the results obtained on experimental plots and in four medium-sized works. The results, which are of particular environmental and pedological interest, recognize this pedotechnique as a specific method for tackling the problems of loss of agroforestry surface area, soil degradation and desertification.

1. Introduction

Soil is subject to a greater decline due to the high levels of exploitation as well as the gradual decrease of natural and agricultural surface areas on a global level, with severe consequences linked to the loss of ecosystem as well as economic functions, which generally go hand in hand. According to the Millennium Ecosystem Assessment (MEA, 2005), the actions needed to contrast the causes and effects of these phenomena, which are becoming more widespread, require two main approaches: the reactive approach, in cases where degradation is developing or is already complete, and the proactive approach to prevent the causes. Considering the nonrenewable nature of soil resources, it is clear how difficult it is to achieve an active approach in solving the loss of agroforestry surface area. With this in mind, a possible approach for reclaiming and managing degraded and compromised soils consists of the production of soil from scratch using recovery technology (for example, physical, chemical or biological techniques in situ), which entails completely or partially restoring the ecosystem to its original state and use, combined with an improvement in its fundamental properties: absorption and exchange, storing and processing organic matter, and availability of nutrients for plants (Bradshaw, 2002; Séré et al., 2010, 2008).

Toward the mid-1990s, pedotechnology began to deal with the study of what were called “artificial soils” or “fabricated soils” by Koolen and Rossignol (1998); the category of artificial soils included all those soils specifically recreated in certain areas (especially urban and industrial ones) to meet specific needs (Capra, 2010). In a short period of time, pedotechnology has become the practice of all anthropic activities that determine, or may determine, man’s growing influence on

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pedogenesis and pedolandscapes, both through the selection and evaluation of suitable materials for constructing soils, as well as the use of processes aimed at modifying soil characteristics, right through to the creation of soils for specific purposes (Capra, 2010).

Therefore, pedotechnology is an intervention aimed at planning and adopting appropriate reactive actions for restoring soils according to their planned use or for creating ad hoc soils (Technosols) using suitable materials derived from human activity (pedomaterials). Such soils must be efficient, sustainable, able to preserve natural resources, consistent with the pedoenvironment, efficient for an undefined time and profitable (Buondonno et al., 2018). In soil restoration interventions, therefore, it is important to consider a suitable project to create a specific Technosol and the selection of suitable pedomaterials (Buondonno et al., 2013; Capra et al., 2011, 2015). Technosols, such as pedomaterials, must be consistent with the environment they are to be inserted into. Therefore, pedomaterials must meet the following requirements: (a) environmental safety and admissibility in the laws in force on the activity of environmental recovery, (b) absence of toxic elements, (c) supply of plant nutrients to promote differentiated plant colonization, and (d) great pedogenetic potential, i.e., the susceptibility to being subjected to alteration/pedogenization to support pedogenetic processes and plant growth (Grilli et al., 2011), i.e., they must tend to mature, transform and evolve toward the soil itself, (e) compatibility with the geological bedrock and pedoclimatic environment of the site to be recovered (Buondonno et al., 2018; Capra et al., 2015), (f) easy availability, and (g) consistent properties.

In 2007, the IUSS Working Group WRB (IUSS Working Group WRB, 2007) presented the classification of soils dominated or strongly influenced by human activity in World Soil Report 103, defining them as Technosols. In this context, the Group of Technosols is thus defined: "Technosols comprise a new Reference Soil Group and combine soils whose properties and pedogenesis are dominated by their technical origin. They contain a significant amount of artifacts (something in the soil recognizably made or extracted from the earth by humans) or are sealed by technic hard rock (hard material created by humans, having properties unlike natural rock). They include soils from wastes (landfills, sludge, cinders, mine spoils and ashes), pavements with their underlying unconsolidated materials, soils with geomembranes and constructed soils in human-made materials. Technosols are often referred to as urban or mine soils".

Reconstitution (Supplementary Material The reconstitution pedotechnique.mp4), which is covered by two patents of the mcm Ecosistemi s.r.l. company that created it (mcm Ecosistemi web site: http://www.mcmecosistemi.com/index.php (accessed on May 2021)), applies a mechanical–chemical treatment to matrices of different origins and natures, modifying their properties and producing new types of artificial soil (Technosol (IUSS Working Group WRB, 2007)) with the desired agroforestry properties. The technology has been supported with European Union Life + 2010 funding (NEWLIFE project web site: http://www.lifeplusecosistemi.eu (accessed on May 2021)) aimed at experimentation to assess its efficiency and feasibility, as well as the development of soil reconstitution in the fight against degradation. The method of the technology is consistent with the "Thematic soil protection strategy" (COM, 2006); moreover, the system fully adopts the circular economy model, since it restores and reproduces a nonrenewable resource (soil) by recovering residues and waste otherwise destined for disposal with huge environmental and economic costs (Timpano, 2016), and it is included in restoration ecology. Based on the abovementioned considerations, reconstitution technology can be included in pedotechniques and, above all, seen as a development of them. Since the reconstitution, in addition to using pedomaterials (matrices) that fulfill the cited requirements, a specific dosage and treatment method provides an alteration and a new conformation of the involved matrices, starting pedogenesis.

The properties of the reconstituted soils and the technical-economic sustainability of the pedotechnology have been demonstrated over the years with agronomical tests and experiments in greenhouses and fields, as well as comparative analysis between degraded soils and reconstituted soils produced from them, demonstrating reconstituted soil's ability to create a stable pedosystem which can carry out its basic functions — agriculture, forestry, storage, filtration, transformation of nutrients and water, and biodiversity pools.

The aims of the paper are to describe:

(a) interventions in medium-sized sites (50000–500000 m^2): To restore degraded soils applying reconstitution to soil site and/or to manage soil sealing using reconstitution to produce fertile Technosols from matrices different from soil;
(b) reconstituted soils in circular economy: In all the presented cases, it has been shown that reconstitution technology offers the possibility to produce suitable soils by using waste, which is available in large quantities;
(c) the sustainability assessment of the technology: The interventions would not have been economically sustainable without the use of reconstitution, both in terms of costs and the poor availability of raw materials (fertile soil), the latter of which could be found only by involving removal from other sites. This is particularly important in cases of soil sealing: The high costs and scarcity of fertile soil and/or lack of available soil often make restoration impossible, leading to the site being permanently abandoned due to insufficient resources available.

2. Material and methods

2.1. Reconstitution

Reconstitution applies a mechanical–chemical treatment to two groups of matrices: (i) primary matrices (matrices I), represented by the main material of the treatment to be converted into fertile soil, for example, degraded soil to be restored to its original fertility conditions, or alluvial deposits of dredging sludge (from dams, reservoirs and canals); (ii) secondary matrices (matrices II) refer to suitable materials and waste from production activities, whose working processes and raw materials used are known. Depending on their nature, secondary matrices are divided into organic and mineral matrices. For instance, organic matrices come from wood and cellulose processing production activities from the textile and agroalimentary industry, and they are characterized by a high organic component with a high carbon/nitrogen ratio, a high presence of plant fibers and other physical–chemical properties of agronomic interest. Mineral matrices come especially from manufacturing processes of the mining industry, the preparation of drinking and industrial water and the management of hydroelectric reservoirs and internal canals: These matrices are characterized by a predominant clayey, silty and sandy, calcareous or chalky fraction.

The reconstitution treatment spans 5 stages.

(1) Dosage formulation
It consists of the chemical–physical and environmental characterization of primary and secondary matrices, which are then selected according to the final type of product to be obtained, and then their dosage is evaluated. The dosage formulation considers the parameters for describing chemical, physical and rheological properties inserted in the calculation application program (PEDOGÉNIA), which enables a theoretical estimate of the chemical properties of the finished product to be generated.
(2) Mixing
The suitably dosed matrices undergo mechanical mixing under controlled humidity conditions.
(3) Breakup
Mixing is followed by breakup by mechanical elements with rotating movements at variable power, depending on the rheological properties of the materials: This operation breaks up, spalls and defibers the mixture.
(4) Polycondensation
During this optional stage, humic components, used for stabilizing the organic matter, can be added in solution form.
(5) Reconstitution
The final stage of reconstitution, consisting of the combined rotating action of other mechanical parts (hammers and discs), is represented by a specifically calibrated cyclic compression of the broken-up product with the consequent formation of new reconstituted soil aggregates.

The treatment generates a finished product with different characteristics and properties than the matrices from which it originated, which is either a soil with restored fertility from a physical, chemical and biological point of view or a Technosol with the desired properties; in both cases, these types of products can be used for restoring degraded soils or for reproducing a layer of fertile soils in areas completely lacking in soil. The actions described carry out some modifications and reconstructions on the matrices; therefore, reconstitution takes on particular importance in that the technologies known today do not involve treatments on pedomaterials aimed at the production of prepedogenized aggregates, but they involve mixing without any specific treatment on their structural and chemical aspects. Therefore, reconstituted soil must not be assimilated with "a geomiscic horizon (from Greek "geo", earth, and Latin "miscere", to mix) developed when, using earthmoving equipment, a moderately thick layer (of at least 30 cm) of different kinds of natural earthy materials is added to the soil and then, for farming purposes, is deeply mixed by heavy machinery with underlying soil" (Dazzi et al., 2009). It is, in fact, a Technosol produced by a targeted dosing of the components to obtain a balanced composition of the chemical–physical properties, by mixing and modifying the components, by actions on the aggregate microstructure and on the soil structure, on the organic matter in relation to the mineral fraction and on its stabilization.

2.2. Intervention sites

The cases described in this paper, carried out since 2008 (Table 1, Fig. 1, Supplementary Material Intervention sites.mp4), refer to studies on experimental plots and on 4 frequently observed conditions where the intervention of reconstitution technology becomes necessary: (i) degraded soil management — Areas 1 and 2: agronomic restoration of degraded soil to restore the chemical and physical fertility, performed by treating the soils of the intervention site; (ii) soil sealing management: Areas 3 and 4: treatment on soils and/or other primary matrices coming from different sites: Area 3 to restore environmental and pedological conditions so that a closed landfill can be reforested (site soil was unusable); Area 4 to make a forest renaturalization on a site previously used as a large construction site where there was no longer a soil layer (site soil was scarce).

In all these cases, the following criteria are met: (a) obtaining soil quality considering physical (texture, bulk density and porosity) and chemical (organic carbon, total nitrogen, pH, cation exchange capacity) characteristics as indicators; (b) saving the non-renewable resource of soil; (c) reducing the effective loss of agroforestry surface area; geo-pedo-compatibility: use of soils from areas adjacent to the intervention area; and (e) developing a new model of circular economy.

The methods used for carrying out analytical determination on soils over the years are described in Appendix A.

Table 1
Type of study, experimental setup and main reconstitution effects on the study Areas.

Study area	Time	Type of study	Experimental setup	Main reconstitution effects	References
Area 1	2008–2013	Physical, chemical	Field: soil temperature fluctuation; maize cultivation pots: maize and tomato cultivation	Water holding capacity, soil temperature, soil fertility	Manfredi (2016), Manfredi et al. (2012b, 2015, 2018, 2019b); http://www.mcmecosistemi.com/news.php?id=87 (accessed on May 2021)
	2011–2013	Physical, chemical, ecological	Plots	Soil structure, Bulk and Particle Density, Organic Carbon	Manfredi et al. (2016a,b, 2019a)
Area 2	2017–2020	Physical, chemical	Field: agronomic restoration	Soil fertility	
Area 3	2011–2019	Physical, chemical, ecological	Field: reforestation	Soil fertility	Giupponi et al. (2013a,b, 2014), Manfredi (2016), Manfredi et al. (2012a, 2014, 2019d,c), Cassinari et al. (2015)
Area 4	2017–2020	Physical, chemical ecological	plots: reforestation pots: *Quercus robur* L. cultivation	Soil fertility	Manfredi et al. (2019e), Meloni et al. (2018)

Fig. 1. Localization of the Study Areas, Italy, in the box the North Italy.

2.2.1. Degraded soil management

2.2.1.1. Area 1: Gossolengo 2008–2013. Area 1 had a surface area of 8 ha in the municipality of Gossolengo (Piacenza), Emilia Romagna region, Italy, located on the right bank of the Trebbia River (coordinates: 45°01'11'' N 9°36'20'' E), 86 m above sea level (Fig. 2).

The site is characterized by poor agricultural productivity due to soil compaction, high surface stoniness, low-thickness soil and poor chemical fertility, such as low organic carbon (organic C), moderately alkaline reaction, low cation exchange capacity (CEC), low availability of elements, high concentrations of total and active limestone together with an overall lack of uniformity of the soils present. The conditions observed at the site were caused by previous gravel extraction activities carried out in the 1980s (1981–1987), reaching a depth of approximately 5 m under the ground. At the end of this extraction, the site was filled with various types of waste, such as demolition and excavation waste and construction waste; the whole surface area was created by making a layer of earthy aggregates of less than 40 cm, with

Fig. 2. Area 1, Gossolengo, Piacenza, Italy, from Google Earth, 2013.

Fig. 3. Area 1, experimental plots, Gossolengo, Piacenza, Italy, from Google Earth, 2011.

soils coming from excavations and waste material produced by the sugar refining industry (calcium carbonate). The aim of the intervention using reconstitution was to improve the physical and chemical properties of the degraded soils present at the site, aiming for more important aspects, such as increasing soil depth, reducing surface stoniness and stones (both in terms of size and quantity), improving structure (from compact to porous), improving workability and hydrological properties (increase in water retention capacity), increasing organic C and the C/N ratio (organic C/total nitrogen ratio), increasing the CEC, reducing the pH, the total and active limestone, and increasing the availability of nutrients.

The reconstituted soil properties were compared with farm soil before the intervention, and two agronomic tests were performed: a field test using maize with different irrigation rates and two pot tests, the first using maize to test plant emergence and root development, and the second using tomato to test plant development.

2.2.1.2. Area 1: Experimental plots Gossolengo 2011–2013. Within Area 1, twenty-four experimental plots ($3 \times 5 \times 0.4$ m^3) were set up above ground to investigate the evolution of the physical and chemical properties of reconstituted soils produced using different types of primary and secondary matrices (Manfredi et al., 2019a) (Fig. 3).

The reconstituted soils were produced by mixing natural degraded soils and/or alluvial sediments and/or alluvial sand (primary matrices) with plant water treatment sludge and/or paper industry sludge resulting from pulp and papermaking (secondary matrices). The primary matrices, taken in a suitable amount from the source (approximately 50 kg each), were moved to the reconstitution site. An aliquot (approximately 30 kg) was used to prepare 10 soil plots, while reconstitution was applied to the remaining plots. The secondary matrices came from 6 Italian paper industries and differed in bulk and particle density, pH, organic C and total N contents. The plots were set up to test their physicochemical properties. The development of Licogala terrestre Fr. and Stemonitis axifera Bull. T. Macr. on the same reconstituted soil plot was also investigated (Manfredi et al., 2016b).

Fig. 4. Area 2, Mortizza, Piacenza, Italy, from Google Earth, 2018.

Fig. 5. Area 2, Mortizza, Piacenza, Italy, from Google Earth, 2019.

2.2.1.3. Area 2, Bosco Pontone 2017–2020. Area 2 covered an overall surface area of 50 ha and is located in the municipality of Piacenza (PC), Emilia Romagna region, Italy, in the district of Bosco Pontone (Mortizza), situated between the Po River to the north and the Nure River to the east (coordinates: 45°05'20" N 9°46'00" E), 45 meters above sea level (Fig. 4).

The site is marked by low productivity derived from the pedological nature of the soil and a low supply of organic matter, which had been the case for a long time. The soil, as well as surface crusting, showed different symptoms of impoverishment, such as loss of structure and poverty of nutrients. The aim of the intervention was to carry out agronomic restoration to obtain improved soil workability to enable increased root development, a reduction in surface crusting, and a strong improvement in hydrological properties and chemical fertility.

The farm soil was characterized before the intervention, and the reconstituted soil properties were investigated for the first time after a period of settlement and surface tillage and during the following year (Fig. 5). Triticum durum Desf. has been sown on the reconstituted soils base to date.

2.2.2. Soil sealing management

2.2.2.1. Area 3 Borgotrebbia 2011–2019. Intervention on Area 2 covered an overall surface area of 20 ha, located in the Campo Santo Vecchio district (Borgotrebbia) in the municipality of Piacenza (Emilia-Romagna region, Italy); situated along the orographic right bank of the Trebbia River (coordinates: 45°04'13" N, 9°39'33" E), 60 m above sea level. It is part of the Trebbia Fluvial Park and partially included in the Site of Community Importance (SCI 4010016 Basso Trebbia) (Fig. 6).

From 1972 to 1985, the whole surface area of the site was used as a landfill for solid urban waste, with a depth between 4 and 5 m. Landfill closure works produced a large, mainly level mound, entirely made up of waste, covered by a thin layer (less than 30 cm) of earthy materials of various origins, which did not enable any kind of renaturalization despite repeated

Fig. 6. Area 3, Borgotrebbia, Piacenza, Italy, from Google Earth, 2012.

Fig. 7. Area 3, Borgotrebbia, Piacenza, Italy, from Google Earth, 2019.

attempts over the years. Potential vegetation consisted of riparian woods of Populetalia albae Br.-Bl. 1935 with lowland oak-hornbeam woods (Meloni et al., 2018; Puppi et al., 2010), natural vegetation had almost completely disappeared due to degraded conditions (Giupponi et al., 2014, 2013b) and was mainly represented by ruderal grasses with a wide geographical distribution, mainly therophytes of Stellarietea mediae. The low water-holding capacity linked to the organic C content, the lack of depth and the compacted structure of the closed-landfill degraded cover soil were related to the presence of this vegetation. The aim of the intervention was to restore environmental and pedological conditions so that reforestation could be carried out.

As the soil was unusable and was a mixture of soils and anthropic materials (inert waste, plastics, sludges of different origins) of decimetric size, it was necessary to use soil from other sites and alluvial sediments as primary matrices.

After placement, the surface of the reconstituted soils was tilled to encourage revegetation and to prepare for tree planting (Fig. 7).

2.2.2.2. Area 4 Vicolungo 2017–2020. Area 4 was 3 experimental plots located in a degraded area owned by SATAP S.p.A. (Turin-Milan A44 motorway concessionaire), in the municipality of Vicolungo (Novara, Piedmont region, Italy, coordinates: 45°27'57'' N 8°28'17'' E), 170 m above sea level (Meloni et al., 2018) (Fig. 8).

For a long time, the site was subjected to building works linked to the construction of a railway line and the modernization of the motorway, which strongly altered the state of the area. The main consequences of the building works were the removal of vegetation, high soil compaction, the presence of demolition material and a thick layer of gravelly material used as a stabilizer to enable heavy vehicles to move and park on the site. Due to these alterations, the evolutionary dynamics of the plant coenoses were blocked. Therefore, the aim of this intervention was to carry out reforestation.

Experimentation with reconstituted soils involved subdividing the site into 4 experimental plots (each one covering approximately 1500 m^2), made up of one plot with original soil and amended with compost, and 3 plots with reconstituted soils created with primary matrices that came from different sites; the plots were specifically designed for different textures (loam, loamy sand and sandy loam). The reconstituted soil thickness was approximately 40–50 cm. The plots were tilled (Fig. 9).

2.3. Soil analysis

They are presented as follows: soil physical data (texture, bulk density and porosity) as slow-change indicators and soil chemical data (pH, organic C and carbon fractionation, total nitrogen, CEC, Olsen phosphorus) as dynamic indicators. The

Fig. 8. Area 4, Vicolungo, Novara, Italy, from Google Earth, 2017.

Fig. 9. Area 4, Vicolungo, Novara, Italy, from Google Earth, 2019.

slow-change and dynamic indicators are constantly monitored and used to describe soil quality and define Land Capability Classification (Klingebiel and Montgomery, 1961) and Fertility Capability Classification classes (Francaviglia et al., 2004). This approach proves particularly useful for identifying changes in conditions before and after the intervention, thus determining the importance of the results from an environmental point of view as well as an agronomic and economic one. Slow-change indicators are suitable for highlighting impacts on soil physical characteristics in the long term, while dynamic indicators are important in the short term to detect initial ecosystem responses. To complete the physical description of soils, data on stoniness, root depth and structure and the Stability Index of every intervention site and a study on annual soil temperature trends carried out in Area 1 are presented.

All the analytical results are shown in Supplementary Material soil sample data.xlsx.

3. Results

3.1. Stoniness, depth, structure and stability index

Frequent superficial stoniness was observed, mainly in the form of stones and rocks, at all the intervention sites except Area 2. This condition was strongly reduced by reconstitution since the treatment involved redistribution of the pebbles, stones and rocks present throughout the new soil profile; a reduction in size through mechanical breaking up into more minute lithoid fragments; and a reduction in the percentage of stones present compared to the total mass of the fine soil fraction. The reconstitution treatment reduced stoniness through sifting and partial break-up, excluding the >100mm size class, and a subsequent fragmentation to fractions > 75 mm. These treatment actions were evident in Area 1, farm/reconstituted soils. There was an increase in soil depth in all interventions, both on degraded soils and

Table 2
Area 4: the three types of Technosols with different texture.

	Sample ID	Sand	Silt	Clay	Texture class
		%			
Area 4	1 R	32	43	25	Loam
	2 R	78	15	7	Loamy sand
	3 R	65	18	17	Sandy loam

1 R: reconstituted loam plot; 2 R: reconstituted loam sandy plot; 3 R: reconstituted sandy loam plot.

soil sealing. In interventions on degraded soils, the increase in thickness involved a change from a shallow depth (25–50 cm) to a moderate depth (60–80 cm). In interventions on soil sealing, it went from a shallow/absent soil thickness (0–25 cm) to moderate/high (50–120 cm). After one year, increases in the root depth layer of > 50% were observed in all the interventions. All the soils involved in the interventions underwent a change in structure, as the treatment works by acting both mechanically, by breaking up the original structure and by reconstitution itself (by compressing the broken-up mixture), as well as chemically, thanks to the addition of organic matter from secondary matrices and its integration with the mineral component.

Area 1, farm/reconstituted soils: The soil structure before intervention was primarily blocky subangular and angular and was secondarily platy, with the presence of cemented calcareous aggregates and the formation of surface crusts with consequent cracking; after treatment, the soil had a granular structure, the formation of crusts and cracking was significantly reduced and disappeared during the first year (Manfredi, 2016).

Area 2: Soils before the intervention were single grain, while afterward, they were granular and moderately developed.

Areas 3 and 4: In the interventions on soil sealing, the primary matrices were alluvial sediments with a generally massive structure; after reconstitution, the soil showed a granular primary structure and a blocky subangular secondary structure.

The structural Stability Index (SI), which indicates the soil structure's resilience to structural degradation, indicated sufficient levels of organic carbon for maintaining structural stability in all areas after the intervention.

Area 1 before the intervention, on farm soil and in the experimental plots: The initial SI of original soils described a degraded structure due to the huge loss of organic carbon or a high risk of structural degradation due to insufficient organic carbon (Manfredi et al., 2016a).

Area 2 before the intervention: Only two samples out of seven showed values indicating sufficient organic carbon for maintaining structural stability, while all the others described a degraded structure due to a great loss of organic carbon.

3.1.1. Slow-change indicators

3.1.1.1. Soil texture. Reconstitution treatment does not act by directly modifying the textural classes, but it may allow their variation, only through the dosage of secondary mineral matrices (sand, silt, clay) added for that specific purpose.

Area 1, experimental plots: Reconstitution affected soil texture in only 4 cases, while in all the reconstituted soils, the content of sand, silt and clay changed compared to soil prior to reconstitution, but texture class remained unchanged (Manfredi et al., 2019a).

Area 1, farm/reconstituted soils: The textural classes have remained comparable with those before the intervention (Manfredi, 2016).

Area 2: Although reconstitution ascertained a decrease in the percentage of clay and silt and an increase in the percentage of sand in three cases, it did not influence the textural classes (Manfredi et al., 2019a).

Area 4: The project foresaw the experimentation of three types of Technosols with different textures; for this reason, by adding specific quantities of sand during the treatment, three soils were produced with the following textures: loam, loamy sand and sandy loam (Manfredi et al., 2019e) (Table 2).

3.1.1.2. Bulk and particle densities and porosity. By modifying the soil structure and increasing the concentration of organic matter, the reconstitution treatment led to a decrease in bulk and particle densities and therefore an increase in porosity (Table 3).

Area 1, experimental plots: In reconstituted soil plots, the mean bulk density reduction was from average original soil value 1303 kg m^{-3} to average reconstituted soil value 691 kg m^{-3}; the mean particle density reduction changed from original soil value 2282 kg m^{-3} to reconstituted soil value 2025 kg m^{-3}; and porosity changed from 43% (original soil value) to 66% (reconstituted soil value) (Manfredi et al., 2019a).

Area 1, farm/reconstituted soils: Reconstituted soils had an average bulk density of 1083 kg m^{-3} lower than soils before the intervention (average value 1640 kg m^{-3}); particle density was on average lower in reconstituted soils (2140 kg m^{-3}) than in original soils (average value 2420 kg m^{-3}); consequently, porosity was higher than the farm soil (average reconstituted soil value 49%; average farm soil value 32%).

Area 2: Reconstituted soils had an average bulk density of 840 kg m^{-3}, which was lower than that of the original soils (average value 1347 kg m^{-3}); the average particle density in reconstituted soils was 2270 kg m^{-3}, which was lower than that of the original soils (average value 2514 kg m^{-3}); as a consequence, porosity was higher than that of the farm soil (average reconstituted soil value 63%, average original soil value 47%).

Table 3
Comparison of Bulk and Particle Densities in Area 1 — experimental plots and farm/reconstituted soil — and Area 2.

	Sample ID	BD	PD
		kg m^{-3}	
Area 1: experimental plots	Mean D	1303	2282
	Mean R	691	2025
Area 1: farm/reconstituted soil	Mean D	1640	2420
	Mean R	1083	2140
Area 2	Mean D	1347	2514
	Mean R	840	2270

D: degraded soil; R: reconstituted soil; BD: Bulk Density; PD: Particle Density.

Table 4
Comparison of pH during the years of observations in Area 1 — experimental plots and farm/reconstituted soil — and Areas 2, 3 ,4.

Time		Sample ID	pH
Year			
2013	Area 1: experimental plots	Mean D	8.1
		Mean R	7.8
2008	Area 1: farm/reconstituted soil	Mean D	8.1
2013		Mean R	7.9
2019	Area 2	Mean D	8.0
		Mean R	7.7
2020		Mean R	7.7
2011	Area 3	Mean D	8.1
2017		Mean R	7.8
2018		Mean R	7.6
2019		Mean R	7.6
2017	Area 4	1 R	7.7
		2, 3 R	8.0
2018		1 R	7.3
		2, 3 R	7.4
2019		1 R	7.7
		2, 3 R	7.7
2020		1 R	7.7
		2, 3 R	7.7

D: degraded soil; R: reconstituted soil; Area 4: 1 R: reconstituted loam plot; 2 R: reconstituted loam sandy plot; 3 R: reconstituted sandy loam plot.

3.1.2. Dynamic indicators

3.1.2.1. pH. Following reconstitution, soils always show pH values with lower subalkalinity than soils before the intervention (Table 4). The secondary matrices used, in fact, generally display a pH 7.5–8; they are dosed on the basis of the reaction value of the primary matrices and due to the high amount of organic matter they contain, which allows them to produce a reconstituted soil with a pH that allows them to have excellent availability of nutrient.

3.1.2.2. Organic carbon, C/N ratio, humic and fuvic acids and humification indices. Reconstituted soil always shows a higher level of organic C, reaching values comparable with Histosols in some cases, thanks to an organic component with a high C/N ratio in the secondary organic matrices used (Table 5). In cases of degraded soil restoration, the increase in organic C proves to be as much as >70% compared to conditions before the intervention. The reconstitution process involves the distribution of the different fractions of organic matter within the mineral matrices, dispersing the flaked fibers from the first phase of breaking up, with the final reconstitution the soluble organic matter exposed to contact with the clay fraction is stabilized within the neo-aggregates. The C/N ratio, humic components and humification indices (HI: humification index; DH: humification degree; HR: humification rate) in reconstituted soils show a trend toward the stabilization of organic components and humification processes by assimilating these technologies into fertile and/or forestry soils (Table 6).

Area 1, experimental plots: In original soils, the mean organic C was 14.1 g kg^{-1}, while in reconstituted soil plots, the mean was 75.3 g kg^{-1} (Manfredi et al., 2019a).

Area 1, farm/reconstituted soil: The organic C content after the intervention changed from an average value of farm soil of 12.1 g kg^{-1} to an average value of reconstituted soil of 43.9 g kg^{-1}.

Table 5
Comparison of Organic Carbon values during the years of observations in Area 1 — experimental plots and farm/reconstituted soil — and Areas 2, 3 ,4.

Time		Sample ID	Organic carbon
Year			g kg^{-1}
2013	Area 1: experimental plots	Mean D	14.1
		Mean R	75.3
2008	Area 1: farm/reconstituted soil	Mean D	12.1
2013		Mean R	43.9
2019	Area 2	Mean D	11.3
		Mean R	40.7
2020		Mean R	56.6
2017	Area 3	Mean R	60.7
2018		Mean R	47.6
2019		Mean R	50.1
2017	Area 4	1 R	46.1
		2 R	41.5
		3 R	32.2
2018		1 R	49.6
		2 R	34.2
		3 R	25.0
2019		1 R	47.3
		2 R	27.3
		3 R	27.3
2020		1 R	42.8
		2 R	27.2
		3 R	28.9

D: degraded soil; R: reconstituted soil; Area 4: 1 R: reconstituted loam plot; 2 R: reconstituted loam sandy plot; 3 R: reconstituted sandy loam plot.

Table 6
C/N ratio, Humification Index, Humification Degree and Humification Rate values during the years of observations in reconstituted soils in Areas 2, 3 ,4.

Time		Sample ID	C/N	HI	DH	HR
Year					%	
2019	Area 2	Mean R	10	1.0	50	21
2020		Mean R	16	0.7	60	18
2017	Area 3	Mean R	13	0.7	58	22
2018		Mean R	11	1.0	50	18
2019		Mean R	11	0.7	58	19
2017	Area 4	1 R	10	0.9	53	19
		2 R	11	0.8	56	18
		3 R	11	0.8	56	17
2020		1 R	11	1.0	50	19
		2 R	13	1.1	47	18
		3 R	9	1.0	49	12

D: degraded soil; R: reconstituted soil; Area 4: 1 R: reconstituted loam plot; 2 R: reconstituted loam sandy plot; 3 R: reconstituted sandy loam plot; HI: Humification Index; DH: Humification Degree; HR: Humification Rate.

Area 2: The organic C content increased during the first year from an average value of degraded soil of 11.3 g kg^{-1} to an average value of reconstituted soils of 40.7 g kg^{-1}; during the second year, the Technosol underwent a further increase from 40.7 g kg^{-1} to 56.6 g kg^{-1}.

Area 3: The organic C supply in reconstituted soils in the first year stood at an average value of 60.7 g kg^{-1}. During the second year of observation, the average supply was 47.6 g kg^{-1}, while in the third year of observation, the average content was 50.1 g kg^{-1}.

Area 4: In the plot with a loam texture, the initial organic carbon value was 46.1 g kg^{-1}, and in the fourth year, it was 42.8 g kg^{-1}. In the plot with a loamy sand texture, the initial value was 41.5 g kg^{-1}, which decreased in the fourth year to 27.2 g kg^{-1}. In the sandy loam plot, the average value at the start was 32.2 g kg^{-1}, and in the fourth year, it was 28.9 g kg^{-1}. With the exception of the first year of observation, these values proved to be far higher than those observed in the plot of degraded soil with the addition of compost.

Table 7
Comparison of Total Nitrogen values during the years of observations in Area 1 — experimental plots and farm/reconstituted soil — and Areas 2, 3 ,4.

Time		Sample ID	Total N
Year			g kg^{-1}
	Area 1: experimental plots	Mean D	1.7
		Mean R	4.0
2008	Area 1: farm/reconstituted soil	Mean D	1.9
2013		Mean R	3.9
2019	Area 2	Mean D	1.3
		Mean R	4.1
2020		Mean R	3.5
2011	Area 3	Mean D	3.0
2017		Mean R	5.0
2018		Mean R	4.4
2019		Mean R	4.6
2017	Area 4	1 R	4.6
		2 R	3.6
		3 R	2.8
2018		1 R	4.4
		2 R	2.9
		3 R	2.1
2019		1 R	3.8
		2 R	2.2
		3 R	2.2
2020		1 R	3.8
		2 R	2.1
		3 R	2.2

D: degraded soil; R: reconstituted soil; Area 4: 1 R: reconstituted loam plot; 2 R: reconstituted loam sandy plot; 3 R: reconstituted sandy loam plot.

3.1.2.3. Total nitrogen. In reconstituted soils, the supply of total nitrogen (Total N) is always optimum and higher than that of the primary matrices; in the first stage, this is linked to the nitrogen supply from some secondary matrices and then to the higher population of free nitrogen-fixing bacteria (Azotobacter spp.) compared to the situation before the intervention, as was observed following some analytical studies (Table 7). Moreover, the high water–holding capacity in reconstituted soils enables them to retain nitrogen compounds by strongly reducing loss through leaching.

Area 1, experimental plots: The mean total N value was 1.7 g kg^{-1} in the original soil plots and 4.0 g kg^{-1} in the reconstituted soil plots (Manfredi et al., 2019a).

Area 1, farm/reconstituted soils: Total N increased from 1.9 g kg^{-1} in soil before the intervention to 3.9 g kg^{-1} afterward.

Area 2: A strong increase was observed in the first year compared to the situation before the intervention (1.3 g kg^{-1} to 4.1 g kg^{-1}); subsequently, the total N content reached average values of 3.5 g kg^{-1}.

Area 3: In the first year of observation, the average total N value was 5.0 g kg^{-1}; in the second year, it was 4.4 g kg^{-1}; and in the third year, it was 4.6 g kg^{-1}.

Area 4: In the loam plot, the total N trend showed a slight decrease from the first to the second year and a subsequent adjustment to values of 3.8 g kg^{-1}. In the loamy sand plot, there was a decrease in values of 3.6 g kg^{-1} through 2.1 g kg^{-1} in the fourth year. The same trend was observed in the sandy loam plot, whose initial total N value was 2.8 g kg^{-1}, while in the fourth year, it was 2.2 g kg^{-1}.

3.1.2.4. Cation exchange capacity. The cation exchange capacity in reconstituted soils always has medium-high values, confirming their high fertility and remarkable capacity to retain nutrients, which guarantees their availability over time and a lower loss through leaching (Table 8). Reconstituted soils are rich in exchangeable magnesium and potassium; potassium is made partly available by the gradual transformation of organic matter. The concentrations of exchangeable sodium did not negatively influence plant growth or soil structure, and it remained below 1.0 cmol $_{(+)}$ kg^{-1}. To confirm this, the ESP parameters (percentage of exchangeable sodium on the exchange complex) and SAR (sodium adsorption ratio in soils) in reconstituted soils were normal.

Area 3: The CEC increased from average values of 34.5 cmol $_{(+)}$ kg^{-1} during the first year to average values of 41.6 cmol $_{(+)}$ kg^{-1}.

Area 4: The CEC in the loam plot in the first year was 31.1 cmol $_{(+)}$ kg^{-1}, and then it increased in the following two years to reach 31.9 cmol $_{(+)}$ kg^{-1}. In the loamy sand plot, the value in the first year was 27.7 cmol $_{(+)}$ kg^{-1}; this value increased to 29.2 cmol $_{(+)}$ kg^{-1} in the fourth year. The sandy loam plot followed the same trend, going from 19.3 to 22.5 cmol $_{(+)}$ kg^{-1}.

Table 8
Cation Exchange Capacity values during the years of observations in reconstituted soil in Areas 3 and 4.

Time		Sample ID	CEC
Year			cmol $_{(+)}$ kg^{-1}
2017	Area 3	Mean R	34.5
2018		Mean R	41.1
2019		Mean R	41.6
2017	Area 4	1 R	31.1
		2 R	27.7
		3 R	19.3
2018		1 R	37.1
		2 R	27.4
		3 R	27.8
2019		1 R	38.4
		2 R	26.1
		3 R	26.1
2020		1 R	31.9
		2 R	29.2
		3 R	22.5

R: reconstituted soil; Area 4: 1 R: reconstituted loam plot; 2 R: reconstituted loam sandy plot; 3 R: reconstituted sandy loam plot; CEC: Cation Exchange Capacity.

Table 9
Comparison of Olsen Phosphorous values during the years of observations in Areas 3 and 4.

Time		Sample ID	Olsen P
Year		cmol $_{(+)}$ kg^{-1}	mg kg^{-1}
2008	Area 1: farm/reconstituted soil	Mean D	61
2013		Mean R	74
2019	Area 2	Mean D	59
2020		Mean R	75
2017	Area 3	Mean R	53
2018		Mean R	57
2019		Mean R	35
2017	Area 4	1 R	64
		2 R	48
		3 R	44
2018		1 R	106
		2 R	84
		3 R	78
2019		1 R	87
		2 R	85
		3 R	76
2020		1 R	62
		2 R	57
		3 R	56

3.1.2.5. Olsen phosphorous. In reconstituted soils, a strong rise in the Olsen phosphorus (Olsen P) supply was observed, and this increase occurred thanks to the supply from the matrices used, together with organic matter that favors its availability (Table 9). Moreover, an excess of active limestone was always observed in all the soils subjected to treatment, and the value of this parameter decreased over time in reconstituted soils; this favored the reduction of the effect of phosphorus retrogradation, thus increasing its availability.

Area 1, farm/reconstituted soils: Olsen P increased in reconstituted soils compared to farm soil, going from 61 mg kg^{-1} in the original soil to 74 mg kg^{-1} in the reconstituted soil.

Area 2: Olsen P in reconstituted soils during the first year of observation had average values of 59 mg kg^{-1} and 75 mg kg^{-1} in the second year.

Area 3: The supply of Olsen P during the first two years of observation was 53 mg kg^{-1} and 57 mg kg^{-1}, and in the third year, it was 35 mg kg^{-1}.

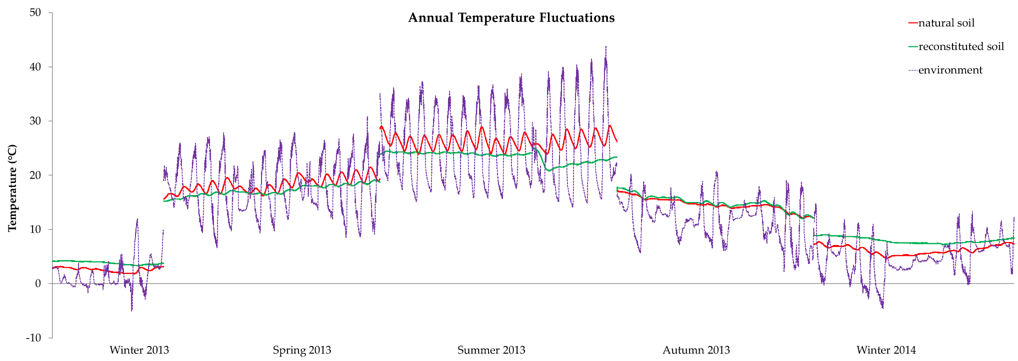

Fig. 10. Area 1, soil temperature fluctuations.

Area 4: Olsen P in the loam plot in the first year was 64 mg kg^{-1}, and this value underwent a further rise to reach 62 mg kg^{-1} during the last analysis. The loamy sand and sandy loam plots showed the same trend: From initial values of 48 and 44 mg^{-1}, respectively, the trend rose to values of 57 and 56 mg kg^{-1} at the last analysis.

3.2. Fertility capability classification

The chemical fertility of reconstituted soils was also calculated and assessed by using the Fertility Capability Classification (FCC). The FCC classes were calculated by assessing the texture data and exchangeable K_2O, P_2O_5 and pH data. These data confirmed that the Technosol presented optimum chemical fertility values.

Area 2: The average FCC of reconstituted soils was class II.

Area 3: The FCC was calculated on 5 soil samples compared before and after the intervention. The FCC classes described soil in the worst classes before the intervention; these classes improved until they reached class I after the intervention (Manfredi et al., 2019d). The FCC classes calculated at all the monitoring points of reconstituted soil showed that the majority of samples were found in class I.

Area 4: The FCC class was I for the loam plot but class II for the loamy sand and sandy loam plots; the comparison with degraded soil with the addition of compost shows how this plot went from class I to class III.

3.3. Land capability classification

The high aptitude of reconstituted soils for agriculture was also confirmed with the determination of the land capability classification (LCC) classes; in this classification, chemical fertility is correlated with the physical properties of the soil.

Area 1, farm/reconstituted soils: The LCC classes of soils before the intervention were VI (soils with severe limitations that make them more or less unsuitable for cultivation and that limit their use mainly to pasture, meadow pasture, woods or nutrition and recovery of local fauna). Following recovery, it changed to class III (soils with severe limitations that restrict the range of crops or require special conservation practices, or both).

Area 3: The cover soil of the dump was in LCC class IV in 3 out of 5 samples (soils with very severe limitations that restrict the range of crops or require particularly careful management, or both) and class VII in the others (soils with very severe limitations that make them unsuitable for cultivation and that restrict their use mainly to pasture, woods or the life of local fauna). Reconstituted soils, however, were all in LCC class II (soils with moderate limitations that reduce the range of crops or require moderate conservation practices) (Manfredi et al., 2019d).

3.4. Soil temperature fluctuations

The chemicophysical properties of reconstituted soils were also confirmed and corroborated thanks to the study on soil temperature fluctuations at 25 cm of depth carried out for a year on reconstituted soils and farm soil in Area 1 (Manfredi et al., 2015). The soil thermal properties are mostly influenced by the particle size distribution, water content, bulk density, porosity and organic C content. With the same weather conditions and soil texture, the higher organic C and porosity in reconstituted soil determined different thermal diffusivities in reconstituted soil. Reconstituted soil always has fewer and more limited temperature fluctuations than farm soil. Compared to farm soil, reconstituted soil had a higher temperature in the winter months and a lower temperature in summer, thus also flattening day–night temperature fluctuations (Fig. 10).

3.5. Agronomic tests and vegetation studies

The analytical results are corroborated by agronomic tests in pots and in the field as well as observations on the development of vegetation carried out to compare degraded soils and reconstituted soils in the intervention areas.

3.5.1. Area 1

3.5.1.1. Experimental plots. Some Myxomycetes (Licogala terrestre Fr. and Stemonitis axifera Bull. T. Macr.) were observed on the surface of reconstituted soil plots from alluvial sand. The presence of Myxomycetes could be due to cellulose, hemicellulose and lignin in the sludge, which can make the trophic, ecological (C/N 23 ± 8) and hydrological conditions suitable for the decomposition processes of organic matter thanks to saprotrophic fungi and bacteria (Manfredi et al., 2016b).

3.5.1.2. Agronomic field test. In Area 1, an agronomic test was carried out with maize to compare the production yields of farm soil and reconstituted soil by varying the quantity of irrigation water. The results of the test showed that there was no significant yield difference between reconstituted and farm soil, but the reconstituted soil water requirement was 45% lower than the farm water requirement (Manfredi et al., 2012b); http://www.mcmecosistemi.com/news.php?id=87 (accessed on May 2021).

Pot tests

3.5.1.3. Pot test on maize. A pot test was carried out with farm soil and reconstituted soil from Area 1 to assess the plant emergence time and maize root development. The results of the test demonstrated that by improving soil fertility (hydrological properties, organic C and nitrogen content) reconstitution had positive effects on plant emergence and root development. Good hydrological properties and high organic C content mean less mechanical opposition for root development (Manfredi et al., 2018).

3.5.1.4. Pot test on tomato. A pot test was carried out with farm soil and reconstituted soil from Area 1 to assess tomato plant development. During the test, plant height and the SPAD value were monitored, while at the end of the test, the fresh and dry weight of the plant, the number of red and green berries and their weight were determined. Plants grown on reconstituted soil had a significantly higher height at 16 and 35 days after transplanting. The leaf SPAD value at inflorescence was greater than that measured on farm soil. Shoot and root fresh/dry weights and the number and weight of red fruits were higher in reconstituted soil. The dynamics of photosynthesis vary according to the development rhythm of the phenological phases. Reconstituted soil allows the early and close attainment of the phenological stages of the tomato plants compared to farm soil. The results – evaluated in terms of fruit yield, showing a significant increase in the number and weight of marketable fruits – indicated that with the reconstitution technique, positive effects can be expected with the improvement of soil degradation and fertility (Manfredi et al., 2019b).

3.5.2. Area 3

In Area 3, during the stages immediately after the intervention, the spontaneous vegetation that grew was monitored: reconstituted soils had begun to be colonized by herbaceous plant species; depending on the observation period, fungal formations appeared together with them and, in spring, Myxomycetes appeared together with them, all of which was observed during the study on plots of reconstituted sandy soil.

Subsequently, in the period from October 2016 to December 2017, over 3000 trees and shrubs of 16 autochthonous species (Acer campestre L., Ulmus minor Mill., Quercus robur L., Carpinus betulus L., Salix alba L., Rosa canina L., Prunus spinosa L., Cornus mas L., Cornus sanguinea L., Ligustrum volgare L., Corylus avellana L., Euonymus europeaus L., Rhamuns cathartica L., Frangula alnus L., Sambucus nigra L., Spartium junceum L.) were planted in the area. All these plants were no more than 2 years old. The 16 species had to improve the ecological conditions and the landscape of the area and had to produce edible fruits for birds, since the area is a resting place for migratory birds. To encourage the plants to take root, the cutting of herbaceous vegetation and a watering program during the dry season were conducted and still continue. Growth monitoring was conducted on the mortality rate, stress symptoms and phenological cycle completion of 10 plant species (trees and shrubs), in 8 plots (20×20 m $= 400$ m^2), in the restored closed landfill during the 12 months following the end of restoration (which was performed using an ecological approach using Landolt's indices and CSR functional strategy). The number of (i) dead plants, (ii) plants showing stress-related symptoms (leaf yellowing and/or plant pathologies), (iii) flowered plants, and (iv) plants producing fruits were collected monthly on every plot. Stress-tolerant and heliophiles ruderal species were best adapted to the restored environment (dead plants: 0%–39%; unhealthy plants: 24%–42%), whereas the most competitive species were the ones with the highest mortality (17%–43%) and stress symptoms (43%–51%) (Manfredi et al., 2019c).

3.5.3. Area 4

3.5.3.1. Greenhouse tests. The reconstituted soil with a loam texture was compared with unmodified soil and with soil with the addition of compost in an experiment in a controlled environment using small Quercus robur L. plants. The plants were irrigated to field capacity, and then no more water was given until the plants died. During the test, the following were monitored: (i) plant growth, (ii) signs of water stress, and (iii) date of plant death. Daily plant growth on the Technosol was comparable to that of the trial with compost, which were both higher than those of unmodified soil. The plants had come under stress at an average of 16 days after irrigation for unmodified soil, 22 days for soil with compost and 30 days with the Technosol. Plant death occurred 10 days after it came under stress in unmodified soil, after 7 days in soil with compost and after 4 days in the Technosol. The calculation of days of survival was approximately 26 days in unmodified soil, 29 in soil with compost and 34 in Technosol. The experiments conducted highlighted the capacity of reconstituted soil to retain water resources and make them available to plants (Manfredi et al., 2019e).

3.5.3.2. In field. In the spring of 2018, a total of 1,120 forest plants, divided among Fraxinus excelsior L., Populus alba L., Ulmus minor Mill. and Crataegus monogyna Jacq., were planted on three plots of reconstituted soil and one with soil and compost. The plants were irrigated, cutting was performed, and constant evaluation was performed to measure plant height and vitality. At the end of the first growing season, the degree of rooting and growth rates of the plants were evaluated. Evaluations of Crataegus monogyna Jacq., Fraxinus excelsior L., Ulmus minor Mill. and Populus alba L. showed how reconstituted soil was a valid substratum in which plants could take root and grow (average vitality >70%, as in the control, and average growth of approximately 51 cm, compared to 44 in the control). The experiments highlighted the effectiveness of reconstituted soil in promoting the growth rates of forest species and in relation to its hydrological properties.

4. Discussion

Environmental and/or agronomic restoration with the use of reconstituted soil falls within what is defined as "restoration ecology", as suggested by Morseletto (2020). Morseletto (2020) explores "restorative" and "regenerative" concepts from the point of view of circular economy, defining how restoration can be considered a core principle because it has widespread applications and can be a point of reference for circular applications. The (Latin) prefix "re" indicates repetition. Restoration is from "(re)staurare", meaning to repair/give back/build up again. Regeneration is from "generare", which means to give birth/generate. "Restorative" is commonly used for describing aspects related to individuals; in contrast, regeneration is frequently employed in sciences such as ecology, biology and medicine to indicate functional self-renewal or, more often, a morphogenic replacement of lost or damaged parts or structures in organisms or ecosystems. Restoration and regeneration are also associated with ideas and frameworks that have influenced or flowed into the circular economy proposition (Craft et al., 2017; Ellen MacArthur Foundation (EMF), 2013; Geisendorf and Pietrulla, 2018; Ghisellini et al., 2016; Pane Haden et al., 2009; Jawahir and Bradley, 2016; Lieder and A., 2016; Torres and Parini, 2019; Yudelson, 2010). These ideas and frameworks include Regenerative Agriculture, Restorative Economy, Regenerative Development and Design, Restorative Environmental Design, Regenerative Building and Cradle to Cradle. In the circular economy literature, restoration is the return to a previous or original state, and it focuses on reversing damage caused by human intervention by proposing a return to an unspecified original condition. Restoration ecology can be a useful adjunct to the development of a circular economy construct; it is a branch of ecology that aims to recover degraded, damaged or destroyed ecosystems (Society for Ecological Restoration Science and Policy Working Group, 2002) through a suite of tools developed within the discipline to accelerate the recovery of damaged ecosystems (Hobbs, 2018; Perring et al., 2015; Rohr et al., 2018). From this point of view, reconstitution can be included in restoration ecology and therefore merges with the concept of circular economy. The basic principle of the circular economy is fully satisfied because the matrices used in the reconstitution process are waste from production activities that are thus transformed into a resource. Furthermore, reconstitution makes it possible to recompose into the soil those matrices produced by it or deriving from its dispersion (e.g., alluvial sediments or dredging sludges: primary matrices; products deriving from industrial mining processes, from management of hydroelectric reservoirs and internal canals: secondary mineral matrices). With reconstitution, therefore, they achieve dual aims, one linked to restoration ecology – to recover degraded, damaged or destroyed ecosystems – and one linked to the extension of the life cycle of products — to reduce the amount of waste that needs to be sourced at the dump.

To assess the sustainability of the reconstitution technology and its applications, it was necessary to consider chemico-physical data, agronomic tests and vegetation studies. It would not have been economically sustainable to achieve the presented results without the use of reconstitution, both due to high costs and scarcity of fertile soil and/or lack of available soil; historically, often the restoration was too costly and challenging and was deemed impossible, leading to the site being permanently abandoned.

The trend of soil fertility allows us to measure the resilience of the reconstituted soil's quality. Considering the fertility parameters of Area 1 and data yields by farmers, since 2008, Technosols have maintained high fertility, so the resilience can be estimated for at least 13 years. Reconstitution technology – due to its environmental, social and economic impacts – is an effective and useful tool in all interventions where necessary. To prepare and locate Technosols, the environmental impact is lower than mining activities and is proportional to the intervention size; furthermore, unlike mine activities, at the end of the recovery, the environmental conditions – fertility and protective soil power – improve. The social impact of agronomic restoration is assessed in increasing productivity and prosperity; degraded and soil sealing interventions allow public usability, so these restoration methods can be considered tools for landscape improvement. In comparison with other environmental recovery techniques, reconstitution interventions have lower economic costs; the advantage is estimated to be 70%. The change in FCC and LCC classes after the interventions indicates an increase in the intensity, adaptation and choice of land uses and in the soil's economic value.

5. Conclusions and future developments

The encouraging results of studies conducted since 2008 have enabled us to continually improve knowledge on reconstituted soils and to reach the awareness of being able to create a Technosol able to solve the problem that made intervention necessary in the first place, based on the environment and the requirements of the site. The trends concerning dynamic and slow-change indicators, other chemicophysical parameters presented and the results of agronomic tests and plant development enable us to assert that reconstituted soils lead the intervention site to a complete restoration of ecosystem function.

Until now, in addition to the continual monitoring of chemicophysical parameters of the reconstituted soil in the 4 Areas described, the ongoing agronomic tests in Area 2 and controls on vegetation in Areas 3 and 4, other activities are being developed thanks to the collaboration between mcm Ecosistemi and various Italian universities and research centers: Tests on reconstitution with the use of mountain dam deposits as primary matrices and studies on the nature of Technosols thus produced through agronomic tests in pots and in the field, lysimeter studies with reconstituted soils made with primary matrix compost produced from dredging sludge and green waste with suitably selected secondary matrices (AGRISED project web site: http://www.lifeagrised.com (accessed on May 2021)), and analytical studies are all being enhanced with studies on microbial biodiversity and permeability. In particular, reconstitution applied to dredging sediments proves to be particularly interesting from the point of view of recovering a matrix considered waste in Italy and could (in the absence of contamination or the presence of heavy metals exceeding the thresholds) present a great resource for the production of soils to be taken to areas subject to soil sealing and is a further step toward circular economy. Furthermore, from the point of view of waste that becomes a resource, new secondary matrices are being continually tested, which could potentially be used in the production of reconstituted soils.

CRediT authorship contribution statement

Paolo Manfredi: Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Visualization, Supervision. **Chiara Cassinari:** Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Marco Trevisan:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Materials and methods

A.1. Physicochemical analysis

Physicochemical properties were performed in triplicate on air-dried samples, ground and sieved to 2 mm. According to the Official Italian procedures (MIPAF, 1997; MIPAF (Ministero delle Politiche Agricole e Forestali), 2000).

To determine particle-size analysis the wet sieving and sedimentation procedure after pre-treatment with hydrogen peroxide to remove organic matter and cementing substances, was made. Textural classes were identified according to Soil Survey Laboratory Methods (2004).

Bulk Density was calculated by weighing a known volume of undisturbed soil at 105 °C.

Particle Density was measured using a pycnometer.

Porosity (%) was calculated as follows:

$$\text{Porosity} = \left(\frac{1 - \text{Bulk Density}}{\text{Particle Density}}\right) \times 100 \tag{A.1}$$

Stability Index (Pieri, 1992) was calculated as follows:

$$\text{S.I.} = [(1.724 \times \text{ org.C\%})/(\text{silt \%} + \text{clay \%})] \times 100 \tag{A.2}$$

The soils water holding capacity was investigated using Richards plates, on disturbed and undisturbed samples.

Soil reaction (pH) was determined in 1:2.5 soil:water suspension after shaking for 2 h by potentiometric method.

Electrical conductivity was determined on saturated paste of soil.

Total $CaCO^3$ was determined with the Dietrich-Fruehling calcimeter.

Active limestone was determined by cold reacting sample with an excess of ammonium oxalate solution. The quantity of ammonium oxalate which has not reacted is evaluated by titration with a potassium permanganate solution.

Total N, Total C and Total S were determined using CHNS Elemental Analyzer.

Organic C was oxidized and analyzed by titration (Walkley and Black, 1934).

C/N was calculated.

The Humic Acids were solubilized by an alkaline solution of sodium pyrophosphate and sodium hydroxide; the Non-Humic fraction (NH) was separated from the Humic Fraction (HA + FA) by Solid Phase Adsorption Chromatography (SPE) on polyvinylpyrrolidone resin. After the separation of Humic Acids by precipitation, the Fulvic Acid fraction was retained by the resin in an acid environment, while the non-phenolic substances remain in solution and can be removed. Subsequently, the adsorbed Fulvic Acids were eluted with a sodium hydroxide solution. The extracts were titrated with iron (II) sulfate solution.

NH, HI, DH and RH were calculated as follows:
TEC = Total Extractable Carbon
CH = Humic Carbon

$$NH = TEC - (HA + FA) \tag{A.3}$$

$$HI = \frac{TEC - CH}{CH} \tag{A.4}$$

$$DH = 100 \times \frac{CH}{TEC} \tag{A.5}$$

$$RH = 100 \times \frac{CH}{TOC} \tag{A.6}$$

Available P was determined with spectrophotometer following Olsen method.

Cation Exchange Capacity (CEC) was determined with the barium chloride–triethanolamine method buffered at pH 8.2, the solution was titrated with EDTA; exchangeable bases were determined with Atomic Absorption Spectrophotometer (AAS).

ESP and SAR were calculated as follows:

$$ESP = \frac{Na^{+}}{CSC} \times 100 \tag{A.7}$$

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{A.8}$$

Available Fe and Mn were determined following (Lindsay and Noewell, 1969) method.

Metals were extracted in aqua regia on a heating plate, and they were detected with Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

A.2. Fertility capability classification

Soil chemical fertility was calculated by texture, Exchangeable K_2O, P_2O_5 and pH; chemical fertility decreases from 1 to 5. Soil intrinsic fertility was calculated by organic matter, annual mineralization coefficient (depending on clay and total limestone; (Francaviglia et al., 2004); intrinsic fertility decreases from A to C. Soil global fertility was inferred from chemical and intrinsic fertility classes; global fertility decreases from I to V.

A.3. Land capability classification

Land Capability Classification (Klingebiel and Montgomery, 1961) refers to soil physical properties, which determines its more or less attitude for crops, as regards the limitations to agricultural use in general. The limitations derive from the soil quality, but also from the physical landscape — morphology, climate, vegetation. LCC links also to soil chemical fertility parameters (pH, CEC, organic matter, Electrical Conductivity, saturation in bases). LCC classes decreases from I to VIII. The assigned soil class is the worst class from the single parameters.

A.4. Soil temperature

To measure soil temperature, at 25 cm depth, two detection probes (AHLBORN ALMEMO 2390-8) were used; both connected to a data logger measuring data every 10 min.

A.5. SPAD values

Leaf chlorophyll content was measured using a Soil Plant Analysis Development (SPAD) Chlorophyll Meter (SPAD-502 Konica Minolta).

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2021.102246.

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