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Growth and yield response of tomato (*Solanum lycopersicum* L.) to soil reconstitution technology

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SUMMARY. – A reconstituted soil, derived from mechanical and chemical treatments of a Technosol mixed with organic matrices, was evaluated as a suitable soil for tomato growth. The physico-chemical properties of the reconstituted and original soils were analysed, and SPAD readings and plant height related to the phenological stages, as well as yield of the whole plant and fruits at maturity were also measured. Reconstitution increased soil porosity, water holding capacity, organic carbon and total nitrogen. Plants grown in the reconstituted soil had a statistically higher height at 16 and 35 days after transplanting. Leaf SPAD value at the emergence of inflorescence was also greater than that measured in the original soil. Shoot and root fresh/dry weights, and number and weight of red fruits were also higher under the reconstituted soil. The results indicate that with the reconstitution technique positive effects can be expected on the improvement of soil degradation and fertility, resulting in better tomato yield.

INTRODUCTION. – Soil is a dynamic, living, natural body, it is vital for the correct functioning of terrestrial ecosystems, and represents a unique balance among physical, chemical and biological factors (PANKHURST *et al.*, 1997; SHUKLA and VARMA, 2011; MARINARI *et al.*, 2015). In the last century, humans started cultivating land intensely to produce plants for food, thus causing a depletion of natural resources and an environmental degradation (PANKHURST *et al.*, 1997). Soil degradation is defined as the diminishing capacity of the soil to provide ecosystem goods and services (FAO, 2015). Soil degradation is frequently confused with land degradation, which concerns a more holistic phenomenon related to the loss of productivity of ecosystems, biodiversity and water quality, which may or may not include soil degradation. Soil and land degradation strongly affect the efficiency of agriculture (CARRERA *et al*, 2007; NACHTERGAELE *et al.*, 2011). The major drivers of soil degradation are climate dryness

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(D'ODORICO *et al.*, 2013), unsustainable agricultural practices, industrial and mining activities (FAO, 2006), expansion of crop production to fragile and marginal areas (SHANGGUAN *et al.*, 2014), inadequate maintenance of irrigation and drainage networks, and overgrazing (HOOKE *et al.*, 2012). Fertile soils with good physical and chemical properties to support root growth are essential for sustainable agriculture, but, since 1945, approximately 17% of vegetated land has undergone human-induced soil degradation and loss of productivity (OLDEMAN, 1994). Intensive agriculture can degrade soils and reduce their fertility in the long-term (SCHMIDT *et al.*, 2011), particularly in the Mediterranean areas where soils are usually low in organic carbon and macronutrient content (CHITI *et al.*, 2011; VACCARI *et al.*, 2015). The growing production demand for crops and the ever-increasing soil degradation process are causing a dramatic rise in the use of fertilizers, stimulants and ripeners aimed at correcting deficiencies in the soil.

Restoring the intrinsic properties of the soil and dealing with its degradation process involve protecting and recovering an important and non-renewable resource in order to improve food production. The European Community supports strategies aimed at protecting soil and stopping degradation and desertification. The LIFE programme funds active projects concerning this issue. The New Life project tests technology aimed at recovering the fertility of low quality, degraded and desertified soils, alluvial sediments and Technosol, in order to prove its effectiveness (FAO, 2006). Such technology is the reconstitution (m.c.m. Ecosistemi Patent). The reconstituted soil is generated by chemical treatments and mechanical disaggregation and reconstitution applied to a mixture of soil/sediment and organic matrices, such as paper industry sludge from primary and secondary treatments. The reconstituted soil has better chemical-physical properties than the one it is generated from (MANFREDI *et al.*, 2019). The following are the most important changes in the reconstituted soil versus the original soil it came from: i) change in structure, i.e. a soil poor in aggregates and in structure, reflecting low organic matter content, is converted into a soil with granular structure which allows an optimal exchange between gaseous, liquid and solid phases, hence supplying higher porosity and lower density; ii) greater water holding capacity and water availability for crops (MANFREDI *et al.*, 2012); iii) higher concentration of nitrogen and organic carbon; iv) lower pH and $CaCO_3$; v) better thermal properties (MANFREDI *et al.*, 2015). A previous pot experiment on maize demonstrated that the reconstituted soil had positive effects on plant emergency rate and root development (Manfredi *et al.*, 2018).

Tomato (*Solanum lycopersicum* L.) is the second most important vegetable crop after potato, with a global production of about 164 million tons of fresh fruit harvested on a 4.7 million hectares surface (FAOSTAT, 2015). The total surface area for tomato cultivation in Italy is about 92,670 ha (ISTAT, 2017), representing the most important vegetable crop (Marinari *et al.*, 2015). Tomato is optimally grown under mild environmental conditions, and on well-drained, sandy loamy soils, with pH values ranging between 6 and 7 (Vaccari *et al.*, 2015). A proper water management is crucial for tomato. Excess water may damage roots and determine the uncontrolled development of pathogens. On the other hand, water stress may cause serious consequences for plant physiology such as blocking photosynthesis. Conventional practices are often used - tillage, mulching and commercial chemical fertilizer, pesticides - in order to obtain high tomato yields (Carrera *et al.*, 2007). This intensive production system can degrade soil quality, enhancing the soil's susceptibility to compaction and crusting, increasing surface runoff and loss of nutrients, and increasing production costs (Rice *et al.*, 2001). Alternative systems using renewable organic resources and/or minimizing tillage have been developed to increase soil organic matter and improve soil quality (Carrera *et al.*, 2007). Therefore, the main aim of this work was to gain additional information on the ability of the reconstitution process to ameliorate the fertility of a former Technosol. The effect of the reconstituted soil was investigated with a pot experiment where soils were cultivated with tomato as the indicator plant.

Materials and Methods. – *Soils*. – A pot experiment was carried out on tomato seedlings comparing the fertility of the Technosol with the reconstituted soil it comes from. The soils were both sampled in a farm near Piacenza. The Technosol is the result of a backfilling (in the 1980s) after gravel extraction activities. Refilling was performed with a silty clay soil from nearby hills, and with waste from the sugar industry (defecation calcium). Such Technosol, 40 cm deep, has low levels of productivity due to its poor agronomic quality - low organic carbon and total nitrogen, C/N ratio revealing mineralization and nitrogen leaching as well as structure deterioration (Manfredi, 2016). In 2008 a Technosol plot was reconstituted. The reconstituted soil was the result of chemical-mechanical treatments applied to the Technosol. In the first phase waste materials of productive activities such as sludge from paper industry and cellulose transformation processes, washing sludge of inert materials and water treatment sediments for drinking water supplies were chemically characterized and thereafter added to the Technosol according to suitable ratios. Secondly, the mixture was crushed, producing a breakdown of the lignocellulosic components and incorporating the organic fraction into the mineral particles of the Technosol. The actual reconstitution phase was then performed by a targeted mechanical compression that gives rise to the formation of the new reconstituted soil aggregates. This treatment allows the organic components, represented by hemicellulose, cellulose, lignin and soluble fractions of organic carbon, to be included in the mineral fraction by means of a defined structural conformation.

Currently, farmland soils are divided into two Technosol and reconstituted plots. For some years now barley, wheat and maize have been growing on these soils, using the same agricultural practices. On May 2015 the Technosol and the reconstituted soil samples were each collected from two different areas of the farm to achieve undisturbed and disturbed soil samples for physical and chemical analyses, respectively.

Physicochemical properties were performed in triplicate on air-dried samples, ground and sieved to 2 mm. According to the Official Italian procedures (MIPAF, 1997, 2000), particle-size distribution was determined by the sedimentation method, and 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:

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

Volumetric water content was determined using Richard plates. pH was measured in H_2O (soil:water 1:2.5) after shaking for 2 h. Organic carbon was oxidized and analysed by titration (WALKLEY and BLACK, 1934). Total nitrogen was measured by the Kjeldahl procedure. Total $CaCO_3$ was determined with the calcimeter of Dietrich-Fruehling. Textural classes were identified according to USDA (SOIL SURVEY LABORATORY STAFF, 2004).

Experimental set-up. – This study was performed in Spring of 2015 at the Research Laboratory of m.c.m. Ecosistemi, Piacenza, Italy. Square pots of 3000 cm^3 volume and 169 cm^2 area were filled with the Technosol and the reconstituted soil. Pots were set-up in fifteen replicates for each treatment and randomly distributed on an insulated surface. One tomato seedling was transplanted per pot on the same day. Fertilisers were applied twice, at transplanting by supplying potassium sulphate (35 g m^{-2}) and ammonium nitrate (14 g m^{-2}). The second application of ammonium nitrate (7 g m^{-2}) was performed at fruit onset. All plants were equally watered with tap and rain water. During the experiment total rainfall was 102 mm. Pots were rotated once a week until the end of the experiment to prevent different sun exposure. At 16, 35 and 63 days after transplanting leaf chlorophyll content was measured using a Soil Plant Analysis Development (SPAD) chlorophyll meter (SPAD-502 Konica Minolta). SPAD readings were taken from the apical leaflet of the youngest fully expanded leaf. Plant height (from the ground to the tip of the plant) was monitored at 16 and 35 days after transplanting. Tomato plants were harvested at 94 days after transplanting. The number and weight of both red and green fruits were determined for each plant. Shoots (stem + leaves) and roots were weighed fresh, and then oven-dried at 70°C to constant weight for dry matter calculation. The stages of inflorescence emergence (first erect bud), flowering and fruit on-set were also observed during the growth period.

Statistical analysis. – The effect of soils on tomato growth parameters and yields was compared by the Student's t-test using the IBM SPSS software package, version 21. When checking the distribution of data and normalization was not possible, means were compared by the non-parametric Mann-Whitney U test.

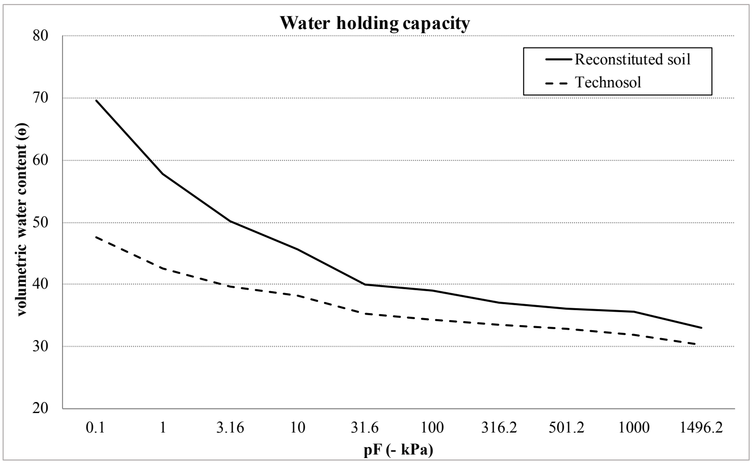

Fig. 1. – Water holding capacity of the soils.

RESULTS AND DISCUSSION. – The reconstituted soil had a higher content of silt (563 g kg^{-1}) and a lower content of clay (107 g kg^{-1}) than the Technosol (498 and 147 g kg^{-1}, respectively), even though the silt loam texture remained unchanged. The physical parameters of the soils are shown in Table 1. After reconstitution the soil showed a decrease in the particle density smaller than the bulk density, resulting in higher soil porosity (49.3%) than the original soil (31.8%). Indeed, the reconstituted soil had a greater water holding capacity, as shown in Fig. 1. Water holding capacity is primarily controlled by the soil texture and the soil organic matter content. As silt- and clay-sized particles of the soils were in comparable amounts, the increase in the water retained in the reconstituted soil for crop use should be ascribed to the addition of organic matter. As can be seen in Table 2, the reconstituted soil had almost four-fold the organic carbon and twice the nitrogen content compared to the Technosol, allowing a C/N ratio typical of a balance between mineralization and humification and organic carbon preservation. On the other hand, variations of pH values and total $CaCO_3$ contents of the soils were negligible. Therefore, the water requirement of the reconstituted soil, because of the highest water availability, was lower than that of the Technosol, as demonstrated during agronomic tests on maize by MANFREDI *et al.* (2012). Reduced irrigations decreased nutrients leaching from the root zone, resulting in a less groundwater contamination and a reduced fertilizer requirement (ALRAJHI *et al.*, 2015).

TABLE 1. – *Physical characterization of the soils (mean ± SE).*

	Sand	**Silt**	**Clay**	**Bulk density**	**Particle density**
	g kg^{-1}			g cm^{-3}	
Technosol	355 ± 25	498 ± 26	147 ± 9	1.64 ± 0.11	2.42 ± 0.08
Reconstituted soil	330 ± 52	563 ± 50	107 ± 46	1.08 ± 0.04	2.14 ± 0.05

TABLE 2. – *Chemical characterization of the soils (mean ± SE).*

	pH	**$CaCO_3$**	**Organic C**	**Total N**	**C/N**
		g kg^{-1}			
Technosol	8.10 ± 0.04	202 ± 16	12.1 ± 1.7	1.87 ± 0.29	6.63 ± 0.72
Reconstituted soil	7.91 ± 0.07	180 ± 29	43.9 ± 5.3	3.93 ± 0.25	11.3 ± 0.75

Plant height measurements were recorded on individual tomato plants at 16 and 35 days after transplanting. Results are shown in Fig. 2 as mean heights. The growth of tomato seedlings was different with different soil treatments. At both growth stages the reconstituted soil produced the tallest plants, which were on average 3 and 8 cm higher than the controls, respectively. These results indicate that a better water availability and soil nitrogen content significantly increased plant height in tomato at different growth stages. Among irrigations, it was also observed that on the Technosol tomato leaves became dry and shrivelled. On the contrary, the reconstituted soil they maintained their turgidity, probably due to an improved efficiency of water supply. On the reconstituted soil inflorescence emergence was higher, and flowering and fruit ripening were earlier than on the Technosol. Fig. 3 shows SPAD readings related to the phenological growth stages of inflorescence emergence, flowering and onset of fruit ripening.

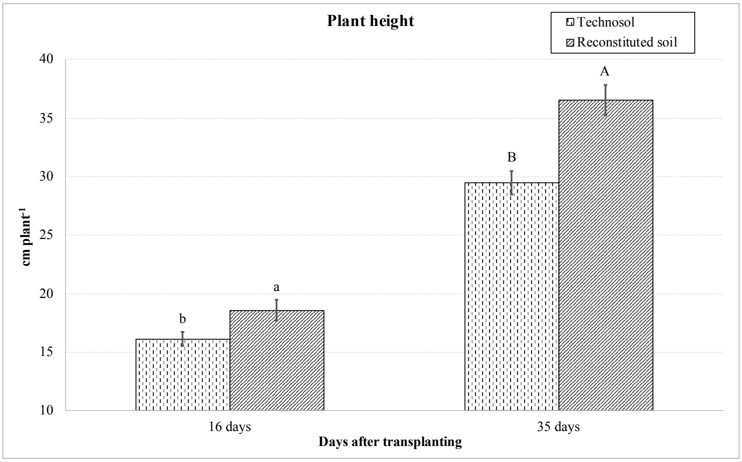

Fig. 2. – Mean height of tomato seedlings at 16 and 35 days after transplanting as affected by the soil treatment. Different italic letters above bars indicate significant differences at $p \leq 0.05$ level, different capital letters indicate significant differences at $p \leq 0.01$ level; error bars indicate SE.

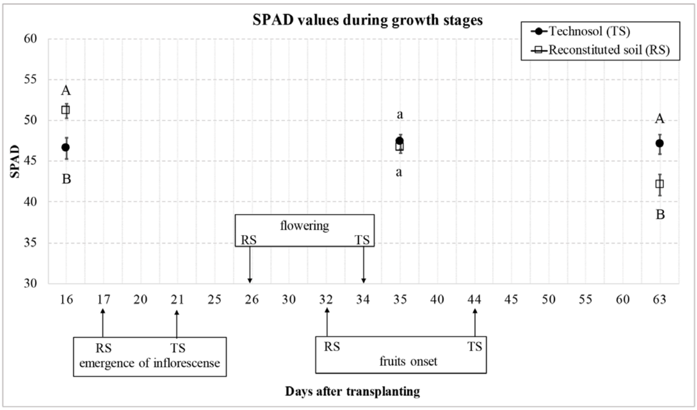

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Fig. 3. – Mean SPAD values in leaf tissues at 16, 35 and 63 days after transplanting as affected by soil treatments. Different letters above bars indicate significant differences at $p \leq 0.01$ level; error bars indicate SE.

The numbers represent the mean day after transplanting. In the reconstituted soil the development of inflorescence occurred 17 days, flowering 26 days and onset of fruit ripening 32 days after transplanting, versus 21, 34 and 44 days in the Technosol. It can be suggested that the reconstituted soil positively affected plant growth, reducing the time among tomato phenological stages. At the inflorescence emergence (day 16) SPAD readings were significantly higher in the reconstituted soil than those recorded in the Technosol, while at flowering (day 35) SPAD value difference was negligible. At full ripening (day 63) SPAD readings were significantly lower in tomato plants grown on the reconstituted soil than on the Technosol. Wood *et al.* (1993) described a link between leaf chlorophyll content, leaf nitrogen status, and crop yield; Soval-Villa *et al.* (2002) found that chlorophyll content is affected by a number of factors including plant genotype, nutrient concentration and nitrogen status of the plant. They reported chlorophyll readings - for each individual cultivar - which were low at the vegetative growth stage, followed by an increase up to fruit development, followed by a drop immediately after fruit development and then remained relatively constant. As can be seen in Fig. 3, the differences among SPAD values confirm this trend and the earlier development of plants in the reconstituted soil. Sixteen days after transplanting chlorophyll values were higher on the reconstituted soil, and at this day both treatments were at the same stage. Thirty-five days after transplanting SPAD readings decreased in the reconstituted soil, while they increased in the Technosol: in the former soil plants were at the phenological stage of fruit development, while in the latter plants were at the flowering stage. Sixty-three days after transplanting SPAD values decreased in the reconstituted soil and plants were at full ripening, while in the Technosol SPAD readings remained unchanged and plants were at the onset of ripening. Tomato plants grown on the reconstituted soil were taller, had larger leaves and produced more fruits than the ones grown on the Technosol, which in some cases developed symptoms of blossom-end rot. The fresh and dry weights of tomato plants were measured at the end of the growth period (Table 3). Tomato plants grown in the reconstituted soil produced the highest shoot (stem + leaves) fresh and dry weights (68 and 15 g plant^{-1}, respectively), along with the highest root fresh and dry weights (23 and 2.1 g plant^{-1}, respectively), which were statistically different from those measured in plants grown in the Technosol. The reconstituted soil also had significant effects on fruit yield: both the total number and the fresh weight of red and green fruits were significantly different in the different soils (Table 4). The reconstituted soils produced twice as many fruits as the Technosol due to the highest number of red fruits. At harvest, the total fruits of the reconstituted soil accounted for 75% of the plant total fresh weight, compared to 62% of the untreated soil. Filgueira *et al.* (2000) related the vegetative and fruits growth, as well as the increase in fruits quantity, to the nitrogen content (Kammoune-Rigane and Medhioub, 2011). Hence, it can be inferred that a higher total nitrogen content and a better C/N ratio in the reconstituted soil could have led to an increase in the overall development of tomato plants and fruits.

Table 3. – *Effect of different soil treatments on fresh and dry weights of tomato plants at 94 days after transplanting (mean ± SE).*

	Fresh weight (g plant^{-1})		**Dry weight (g plant^{-1})**	
	Shoots	Roots	Shoots	Roots
Technosol	36 ± 2.1 B	11 ± 1.1 B	8.0 ± 0.5 B	0.95 ± 0.09 B
Reconstituted soil	68 ± 3.3 A	23 ± 2.5 A	15 ± 0.6 A	2.1 ± 0.21 A

Values in columns followed by different capital letters are significantly different at $p \leq 0.01$ level.

TABLE 4. – *Number and weight of red and green tomato fruits grown on the soils (mean ± SE).*

	Red fruit	**Green fruit**	**Red fruit**	**Green fruit**
	number plant^{-1}		g fruit^{-1}	
Technosol	1 ± 0.3 B	3 ± 0.3 a	34 ± 1.2 b	14 ± 1.2 B
Reconstituted soil	5 ± 0.2 A	3 ± 0.4 a	42 ± 0.9 a	21 ± 1.3 A

Values in columns are statistically different at $p \leq 0.05$ level when followed by different small letters, and significant at $p \leq 0.01$ level when followed by different capital letters.

CONCLUSIONS. – It has been shown that the dynamics of the photosynthesis process varies according to the development rhythm of the phenological phases. The reconstituted soil allows the early and close attainment of the phenological stages of the tomato plants, together with the increase in height and weight compared to the Technosol. The fertility of the reconstituted soil was mainly evaluated in terms of fruit yield, showing a significant increase in the number and weight of marketable fruits. Reconstitution has positively influenced the physical and chemical properties of the original Technosol, producing soils suitable for growing tomatoes. However, to get a full picture of the role of reconstitution in the restoration of degraded soils, further experiments should include the effect of changes of the soil chemical environment on nutrient and trace metal mobility.

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