



# Compost improves plant and soil macronutrient content in a 14-years orchard

Elena Baldi · Martina Mazzon ·  
Luciano Cavani · Maurizio Quartieri ·  
Moreno Toselli · Claudio Marzadori

Received: 14 September 2022 / Accepted: 10 January 2023 / Published online: 16 January 2023  
© The Author(s), under exclusive licence to Springer Nature B.V. 2023

**Abstract** Adequate plant nutritional status and soil fertility preservation can be achieved through sustainable agricultural management techniques. The challenge of intensive orchard cultivation, besides the risk of nutrient decline, is to prevent the loss of soil fertility that could lead to soil degradation with a consequent negative impact on yield and fruit quality. The use of organic amendments could be a sustainable strategy to combine high plant performance with soil fertility improvement. This work aims at shedding light on the effects of compost addition with respect to an unfertilized control and a mineral fertilization treatment on macronutrient (K, Ca, Mg, and S) dynamics in plants and soil of a commercial nectarine orchard planted in 2001. In the first 0.15 m of soil, compost addition resulted in higher values (26–42%) of all the parameters. Both fertilization treatments induced a 28% increase in roots' S content compared to the control but did not induce macronutrient content variation in plant skeleton, pruned wood, and thinned fruits. In autumn leaves, all the macronutrients resulted in higher values (24–45%) with both mineral and compost fertilization, and the same was observed in fruit at harvest (increases of 15–31%). In our study, the treatment with compost satisfied plants'

nutrient demands as much as the mineral fertilizer. In addition, compost treatment also improved soil nutrient content while preserving yield. Our results show that it is possible to reconcile plant nutrient needs with the preservation of soil fertility with the aim of improving sustainability of agriculture.

**Keywords** *Prunus persica* · Soil nutrient availability · Compost · Mineral fertilization · Nutrient removal · Soil macronutrient content

## Introduction

The increasing demand for high-quality nutritional food related to the steady increase in population (El-Jendoubi et al. 2013) is leading to the necessity to maximize yield while minimizing ecosystem impacts deriving from agriculture. According to the report of the Food and Agriculture Organization of the United Nations (FAO 2017), the requirements for adequate food supplies have to pass through sustainable agricultural management techniques. This issue also deals with adequate plant nutritional status and preservation/increase of soil fertility (Toselli et al. 2019a; Zhang et al. 2020). Plant nutrition depends on the nutrient cycle in and out of the orchard ecosystem. The inputs to the soil, for example, include mineral and/or organic fertilizers, atmospheric deposition, and biological nitrogen (N) fixation, while the outputs are represented by harvested fruits, nutrients

E. Baldi · M. Mazzon (✉) · L. Cavani · M. Quartieri ·  
M. Toselli · C. Marzadori  
Department of Agricultural and Food Sciences, Alma  
Mater Studiorum-University of Bologna, Bologna, Italy  
e-mail: martina.mazzon2@unibo.it

lost by leaching, gaseous losses, and erosion (Toselli et al. 2019b). In case of a negative balance between inputs and outputs, the soil would come across a nutrient depletion that, in the long term, would lead to an unsustainable farming system (El-Jendoubi et al. 2013). The challenge of intensive orchard cultivation is, besides the risk of nutrient decline, the loss of soil fertility (both chemical and biological) that could lead to soil degradation (i.e. loss of soil organic matter, erosion, acidification, and pollution) with a consequent negative impact on plant performances (Zhang et al. 2020). Thus, the great challenge for modern farmers is to maintain and/or increase soil fertility in a sustainable way. This could be reached through the application of organic amendments (i.e. composts, biochar, and manures) that are widely recognized to be inexpensive, to release nutrients through mineralization slowly, and to enhance soil carbon (C) and organic matter increase (Mazzon et al. 2018; Sciubba et al. 2015) thus stimulating carbon dioxide sequestration. In addition, the application of organic matter can improve soil physical properties (Chatzistathis et al. 2020) as, for example, bulk density reduction and aggregate stability and water holding capacity increase (Adugna 2016), positively affecting soil microbial community (Fawzi et al. 2010; Safaei Khorram et al. 2019) and increasing macro- and micronutrient availability (Baldi et al. 2021a; Fawzi et al. 2010). Organic amendments thus represent not only a source of N, phosphorus (P), and potassium (K) but also of calcium (Ca), magnesium (Mg), and sulfur (S) which are equally considered essential plant macronutrients (Barreto et al. 2021; Shiwakoti et al. 2020). In the study of Shiwakoti et al. (2020), the long-term (approximately 64 years) addition of farmyard manure (at the rate of  $11.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) evidenced higher macronutrient (K, S, and Mg) content in soil than the other treatments (pea vine and wheat residues, with and without N addition) mainly due to the high amounts of these nutrients that directly contribute to soil chemical fertility. Shiwakoti et al. (2020) also highlighted that manure could have activated soil cation exchange sites releasing organic colloids and consequently adsorbing K to the exchangeable sites and increasing its availability.

Macronutrient soil availability throughout the growing season is fundamental for fruit trees. In a study on pomegranate nutrient dynamics, Maity et al. (2019) demonstrated that plant needs were mostly

satisfied by uptake from the soil more than from the mobilization from plant reserves; as a consequence, if soil nutrients are not replenished through appropriate fertilization management, fruit yield and quality could be severely impaired. In a different study on various fruit trees (i.e. apple, peach, and mandarin), Cruz et al. (2019) showed that adequate K supply at fruit set is of fundamental importance for the final fruit quality. Maity et al. (2019) evidenced that a great amount of Mg was remobilized from leaves to fruit at the maturity stage, while S was mainly concentrated in shoots and Ca in the woody organs of pomegranate. El-Jendoubi et al. (2013) found that K, P, and N mainly accumulate in fruits, while Mg and Ca in abscised leaves. Moreover, it is estimated that peach trees in commercial orchards have a macronutrient requirement accounting for  $74\text{--}425 \text{ g K tree}^{-1}$ ,  $25\text{--}518 \text{ g Ca tree}^{-1}$ , and  $9\text{--}74 \text{ g Mg tree}^{-1}$  (Baldi et al. 2021b) every year. The key issue for fruit tree nutrition is the availability of nutrients in the soil during the entire vegetative season, consequently, the use of organic amendments, that gradually release nutrients through mineralization, could be a sustainable strategy able to combine elevated plant performance with the improvement of soil fertility (Baldi et al. 2021b).

This manuscript follows three previous publications on C (Baldi et al. 2018), N (Toselli et al. 2019b), and micronutrients in the same experiment (Baldi et al. 2021a), and aims at shedding light on the macronutrients K, Ca, Mg, and S. Indeed, the goal of the present study was to determine the effects of the long term mineral fertilization and compost addition in a nectarine orchard (14 years) on 1) soil macronutrient content at the end of the 14-years life-time of the orchard, 2) macronutrient content in different plant organs, and 3) the relation between plant and soil macronutrient content.

## Materials and methods

### Orchard description and treatments

The experiment was carried out on a commercial nectarine orchard [*Prunus persica*, Batsch var. *nucipersica* (Bockh.) Schn.] planted in 2001 (Table 1). The orchard was located in the Po valley (Italy) near Ravenna ( $44^{\circ}27' \text{ N}$ ;  $12^{\circ}13' \text{ E}$ ), an area characterized

**Table 1** Nectarine orchard main characteristics and management strategies (Baldi et al. 2021a, 2018; Toselli et al. 2019b)

Management	Description
<i>Variety and rootstock</i>	Stark RedGold, grafted on hybrid GF677 ( <i>P. persica</i> × <i>P. dulcis</i> )
<i>Training system</i>	Delayed vasette, distance of 5 m between the rows and 3.8 m between trees along the row
<i>Irrigation</i>	Drip irrigation system from June to September (vegetation season)
<i>Phytosanitary treatments</i>	According to crop management guideline of the region Emilia-Romagna ( <a href="http://www.regione.emilia-romagna.it">www.regione.emilia-romagna.it</a> )
<i>Soil management</i>	Tree row was tilled superficially for weed control Alleys were covered with spontaneous grass managed by mowing it 3 times a year
<i>Fertilization treatments</i>	Mineral fertilization (MIN) Nitrogen (N) applied every year at the rate of 70 kg ha <sup>-1</sup> yr <sup>-1</sup> (60% in May and 40% in September); in 2004, N rate was increased to 120 kg ha <sup>-1</sup> yr <sup>-1</sup> and from 2006 to 130 kg ha <sup>-1</sup> yr <sup>-1</sup> . Phosphorus (P) at 100 and potassium (K) at 200 kg ha <sup>-1</sup> (applied only at planting). Rate established according to integrated crop management guideline of the region Emilia-Romagna ( <a href="http://www.regione.emilia-romagna.it">www.regione.emilia-romagna.it</a> ) Nitrogen was applied as ammonium nitrate (N=35%), while P and K were applied as a binary fertilizer (P=10%; K=20%); no other nutrients were provided with mineral fertilization Compost (COM) Applied at a rate of 10 t DW ha <sup>-1</sup> yr <sup>-1</sup> , equal to 240 kg N ha <sup>-1</sup> yr <sup>-1</sup> Compost was obtained from domestic organic wastes (50%) mixed with pruning material (50%) after a 3-month stabilization. Average characteristics: DW of 73%, pH 9, EC 2.96 mS cm <sup>-1</sup> , C/N ratio 10.2, and (in g kg <sub>DW</sub> <sup>-1</sup> ) organic C 234, N 21.1, P 4.8, K 15.2

by a temperate climate and a silt-loam soil (Calcic Cambisol) with a total carbonate content (% CaCO<sub>3</sub>) of 31 ± 1 and an active carbonate content (% CaCO<sub>3</sub>) of 13 ± 1 (Baldi et al. 2021a, 2018). The planting layout and main orchard management strategies are reported in Table 1. Since orchard plantation, three fertilization treatments were compared with four replicates (4 trees each) according to a complete randomized block design: unfertilized control (CK); mineral fertilization (MIN); and compost (COM). Specific information regarding the treatments is reported in Table 1. Fertilizers were applied to the tree row and tilled into the soil to a depth of 0.25 m, while pruned wood was left into the ground and chopped (Baldi et al. 2021a, 2018; Toselli et al. 2019b).

#### Plant sampling and analysis

In 2014, after 14 years of life, 4 trees per treatment were harvested and divided into organs as described by Baldi et al. (2021a, 2018) and Toselli et al. (2019b). Briefly, thinned fruits were collected in spring and weighed, and a representative sample was oven-dried and milled (2 mm). In July, a sample of 40 young fully expanded leaves was collected from the apical part of shoots, and the leaf area was measured

by a portable area meter (Li-3000, LiCor inc., Lincoln, Nebraska). Leaves were then washed, oven-dried, and milled at 2 mm. At harvest, in August, plant yield was recorded; afterward, fresh weight (FW) and dry weight (DW) of flesh and kernel were measured on a representative sample of fruits; dried flesh and kernel were weighted and milled. In September, one tree per plot was enclosed into a plastic net to collect autumn leaves that were weighed, leaf area measured, dried, and milled. In December 2014, at the end of the commercial life of the orchard, the same trees were harvested, divided into roots, trunks, branches (age > 2 years), and current year shoots (twigs), and weighed. A subsample of each organ was oven-dried, weighed, and milled. Roots were washed with deionized water to remove soil residues.

A sample (0.3 g) of each plant organ was mineralized according to the US EPA Method 3052 (Kingston and Jassie 1988) in an Ethos TC microwave (Milestone, Bergamo, Italy), filtered (Whatman 42<sup>®</sup>), and analyzed for Ca, K, Mg, and S by inductively coupled plasma optical emission spectrometer (ICP-OES; Ametek Spectro, Arcos, Kleve, Germany). Blank and certified reference materials (NIST standard reference material SRM 1573a tomato leaves and SRM 1570a spinach leaves) analyses were performed. Relative uncertainty, calculated as the relative deviation of the

measured element concentration to its certified value, was typically better than  $\pm 5\%$ .

The mineral content in different parts of the plant (leaves, fruits, branches, trunk, and roots) was calculated by multiplying each mineral concentration by the DW of the specific organ.

The biomass of the skeleton was calculated as the sum (without pruning wood) of trunk, branch, and twigs > 2 years (identified according to their insertion into branches) measured at the end of the experiment. Skeleton and root nutrient content were divided by the age of the orchard (13) assuming a constant annual increase of weight and nutrient accumulation, and considering the increase of the first year (2001) was negligible since orchard was planted at the end of the year.

### Soil sampling and analysis

In December 2014, an 80 cm deep soil core (70 mm diameter) was collected in the row of each plot with a soil column cylinder auger that was inserted into the soil using a tractor. The core was carefully removed from the auger and divided into four parts according to depth: 0–0.15, 0.16–0.25, 0.26–0.45 and 0.46–0.65 m. Soil from each depth was separately weighted and oven dried at 105 °C for 24 h to evaluate soil bulk density (BD) which was calculated as the ratio between DW and the volume of each core. In addition, soil samples were collected, always in the row, with an auger at 0–0.15, 0.16–0.25, 0.26–0.45, and 0.46–0.65 m depth. Each sample (made of 4 sub-samples) was sieved (2 mm), cleaned from roots and visible plant residues, and air-dried or stored at 4 °C. A sub-sample was then used to evaluate soil total concentration of Ca, K, Mg, and S. Briefly, samples were subjected to wet mineralization by treating 0.5 g of dry sample with 6 mL of hydrochloric acid (37%), 2 mL of nitric acid (65%) and 2 mL of hydrogen peroxide (30%) in an Ethos TC microwave lab station (Milestone, Bergamo, Italy) according to the methods ISO 12914:2012 and 22036:2008. Solutions were filtered (Whatman 42<sup>®</sup>) and the element concentration was determined by inductively coupled plasma optical emission spectrometer (ICP-OES; Ametek Spectro, Arcos, Kleve, Germany). Blank and certified reference material (BCR reference material No 141R calcareous loam soil) analyses were performed; relative uncertainty, calculated as the relative

deviation of the measured element concentration to its certified value, was typically better than  $\pm 5\%$ . Soil pseudo-total mineral element content at the end of the orchard life-time was calculated by multiplying the nutrient concentration by the soil bulk density at the respective depth intervals. Electrical conductivity (EC) was measured on a suspension of 10 g of fresh sample and 20 mL of deionised water that was stirred for 120 min at 25 °C and filtered before measurement. Soil potential cation exchange capacity (CEC) was estimated using the ammonium acetate method (Sumner and Miller 1996).

### Statistical analysis

After assumption verification (Shapiro–Wilk for normality and Bartlett for homogeneity of variance), plant organ data were analyzed with a one-way ANOVA with treatment as a factor (three levels: unfertilized control, mineral fertilization, and compost). Whether necessary, data were transformed using the Box-Cox procedure to fit the ANOVA assumption. Similarly, data on macronutrient content for autumn and summer leaves were analysed with a one-way ANOVA with season as a factor. When significant differences occur ( $P < 0.05$ ), an HSD post-hoc test (Tukey's test) was applied to separate the means. A Principal Component Analysis (PCA) was carried out using plant organ data showing significant differences in the treatments. Soil data were analyzed using a split-plot design, with treatments (three levels: unfertilized control, mineral fertilization, and compost) as the main factor and sampling depths (four levels: 0–0.15, 0.16–0.25, 0.26–0.45, 0.46–0.65 m) as the sub-factor. ANOVA assumption verification and means separation were performed as described for plant organs (R Core Team 2021).

## Results

Fertilization treatments, no matter which one, induced on average a 28% increase in roots' S content compared to the control (Table 2). The fertilization treatments did not induce a variation of Ca, K, Mg, and S content in the plant skeleton, pruned wood, and thinned fruits (Table 2). On the contrary, all the considered macronutrients (Ca, K, Mg, and S) increased in autumn leaves (in a range from 24 to 45%) by both

**Table 2** Macronutrient content (g plant<sup>-1</sup>) in plant organs ± standard error (based on field replicates)

Plant organs	Treatments	Ca	K	Mg	S
Pruned wood	CK	26 ± 1	9.9 ± 0.7	2.2 ± 0.2	1.4 ± 0.1
	MIN	43 ± 1	17 ± 1	3.5 ± 0.3	2.5 ± 0.1
	COM	30 ± 7	13 ± 3	2.6 ± 0.6	1.9 ± 0.4
	<i>P value</i>	0.150	0.098	0.178	0.097
Thinned fruits	CK	0.62 ± 0.14	2.6 ± 0.6	0.29 ± 0.07	0.27 ± 0.06
	MIN	0.44 ± 0.12	2.0 ± 0.6	0.22 ± 0.06	0.21 ± 0.06
	COM	0.87 ± 0.17	3.5 ± 0.7	0.38 ± 0.07	0.36 ± 0.07
	<i>P value</i>	0.168	0.257	0.259	0.251
Fruit at harvest	CK	2.3 ± 0.2	43 ± 1 <sup>b</sup>	3.6 ± 0.1 <sup>b</sup>	2.0 ± 0.1 <sup>b</sup>
	MIN	2.4 ± 0.1	51 ± 2 <sup>ab</sup>	4.8 ± 0.3 <sup>a</sup>	2.8 ± 0.1 <sup>a</sup>
	COM	2.4 ± 0.2	57 ± 1 <sup>a</sup>	4.8 ± 0.2 <sup>a</sup>	2.8 ± 0.1 <sup>a</sup>
	<i>P value</i>	0.867	0.010	0.012	0.006
Autumn leaves	CK	118 ± 3 <sup>b</sup>	43 ± 2 <sup>b</sup>	14 ± 0.3 <sup>b</sup>	2.6 ± 0.2 <sup>b</sup>
	MIN	181 ± 23 <sup>a</sup>	70 ± 7 <sup>a</sup>	21 ± 2 <sup>a</sup>	4.7 ± 0.5 <sup>a</sup>
	COM	156 ± 9 <sup>a</sup>	66 ± 4 <sup>ab</sup>	19 ± 2 <sup>a</sup>	4.5 ± 0.4 <sup>a</sup>
	<i>P value</i>	0.010	0.026	0.012	0.013
Roots	CK	21 ± 3	5.6 ± 0.2	3.0 ± 0.5	0.32 ± 0.02 <sup>b</sup>
	MIN	21 ± 4	5.2 ± 0.5	3.0 ± 0.5	0.43 ± 0.03 <sup>a</sup>
	COM	24 ± 0.3	6.1 ± 0.7	3.6 ± 0.2	0.45 ± 0.03 <sup>a</sup>
	<i>P value</i>	0.771	0.313	0.659	0.001
Skeleton	CK	45 ± 2	12 ± 1	3.8 ± 0.3	1.8 ± 0.1
	MIN	60 ± 7	16 ± 2	5.2 ± 0.7	2.4 ± 0.2
	COM	56 ± 7	17 ± 1	5.0 ± 0.6	2.5 ± 0.2
	<i>P value</i>	0.328	0.220	0.329	0.126

Different lowercase letters indicate significant ( $P < 0.05$ ) differences between treatments  
 CK unfertilized control,  
 MIN mineral fertilization,  
 COM compost

**Table 3** Macronutrient concentration (g 100 g<sub>DW</sub><sup>-1</sup>) ± standard error (based on field replicates) in leaf sampled in summer

Treatments	Ca	K	Mg	S
CK	2.2 ± 0.1	1.2 ± 0.04	0.44 ± 0.01 <sup>a</sup>	0.16 ± 0.03
MIN	1.9 ± 0.1	1.1 ± 0.01	0.39 ± 0.01 <sup>b</sup>	0.15 ± 0.01
COM	1.9 ± 0.1	1.2 ± 0.04	0.39 ± 0.01 <sup>b</sup>	0.15 ± 0.01
<i>P value</i>	0.088	0.088	0.013	0.947

Different lowercase letters indicate significant ( $P < 0.05$ ) differences between treatments  
 CK unfertilized control, MIN mineral fertilization, COM compost

mineral and compost fertilizations. Similar results in the two fertilization treatments (with increases between 15 and 31%) were observed in fruit at harvest with the exception of Ca content that did not show any differences among treatments (Table 2).

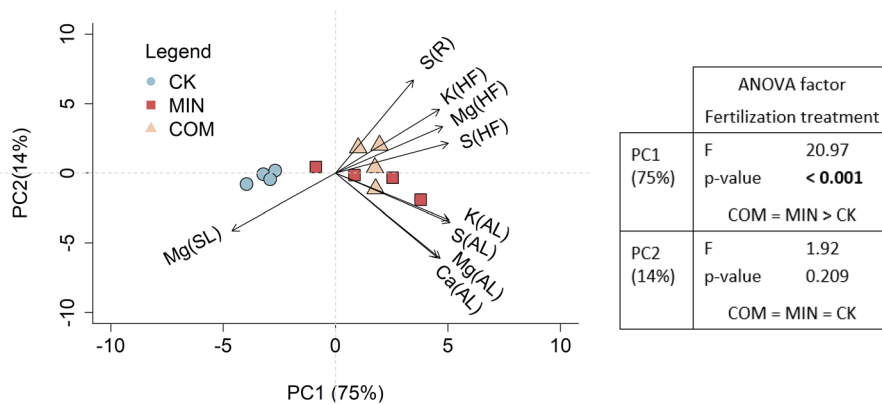
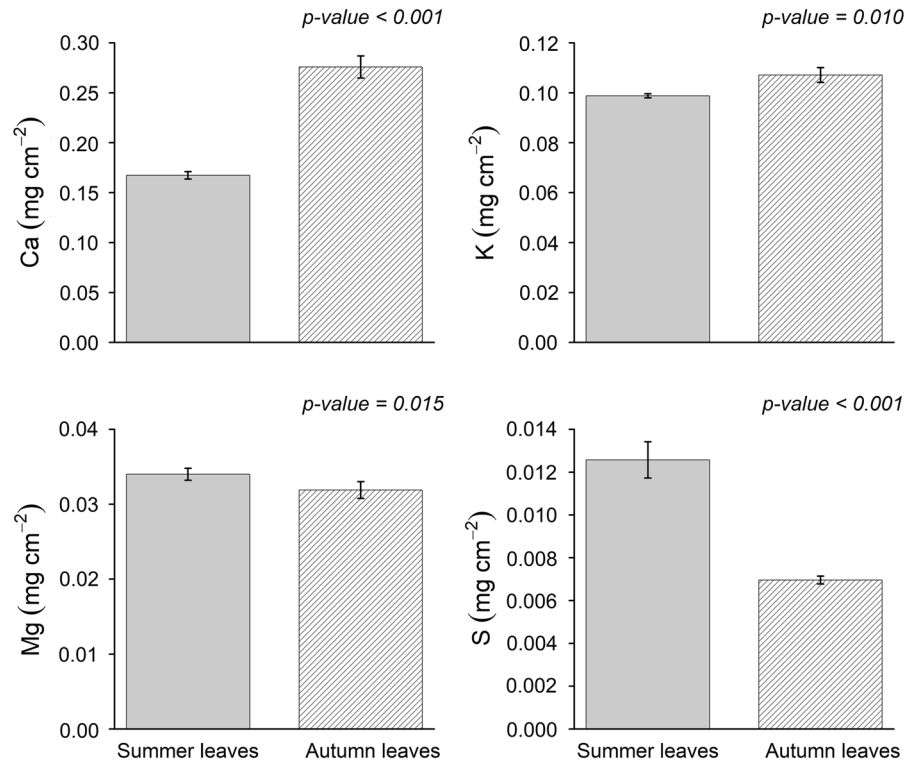
No significant differences between fertilization treatments were observed in the concentration of nutrients in summer leaves (Table 3); the only

exception was Mg which resulted in a 13% higher concentration in the control compared to the two fertilization strategies (Table 3).

The comparison of macronutrient content in autumn and summer leaves highlighted the significant impact of the phenological state for all four macronutrients considered in this study (Fig. 1). Specifically, higher concentrations of Ca and K were observed in autumn than in summer leaves; the opposite was observed for Mg and S.

A PCA (Fig. 2) was performed using data from those organs whose macronutrient content was significantly affected by the fertilization treatments (Table 2). The treatments clustered in two main groups (according to PC1 ANOVA results): the unfertilized control on the left side of the plot, and the two fertilization strategies (mineral and compost) on the right side of the plot. These two groups showed to be clearly defined by the Mg content in summer leaves that characterized the unfertilized control group (Fig. 2). A clear separation in plot space was also

**Fig. 1** Means of summer and autumn leaf content of calcium (Ca), potassium (K), magnesium (Mg) and sulfur (S). Error bars represent the standard error (based on four leaf samples collected in field replicates) and the significant differences ( $P < 0.05$ ) are reported



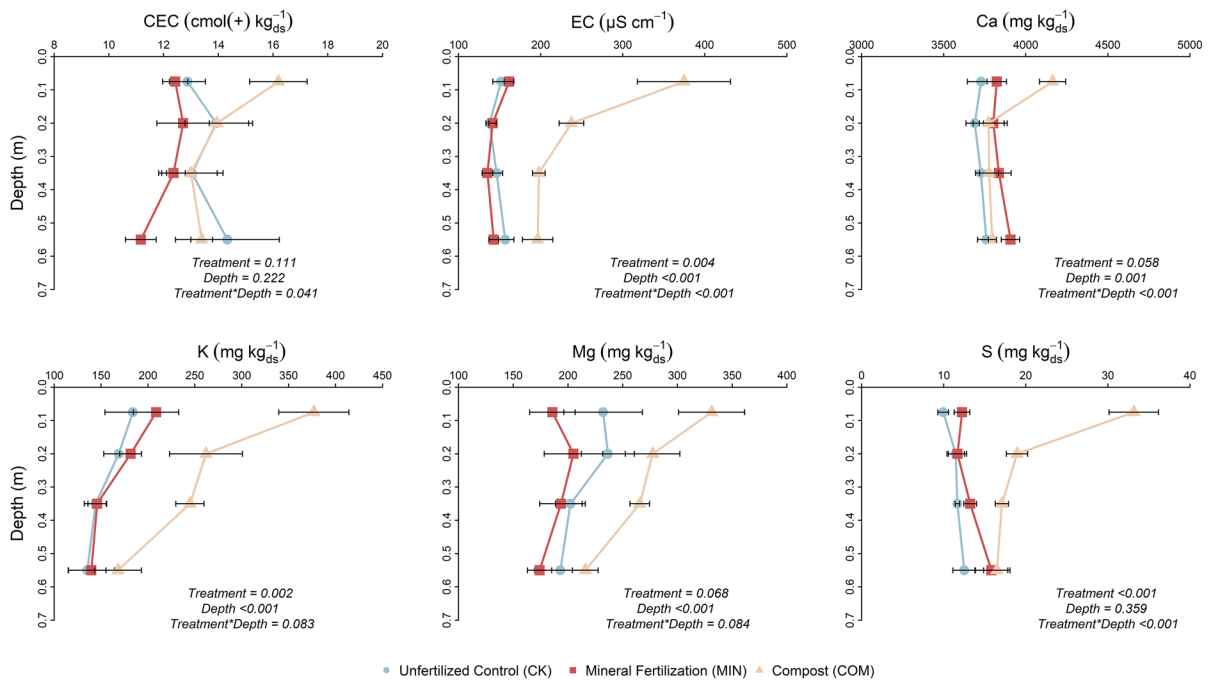
**Fig. 2** Principal component (PC) analysis with macronutrient content (calcium (Ca), potassium (K), magnesium (Mg) and sulfur (S)) in the most relevant plant organs: harvested fruits (HF), roots (R), autumn leaves (AL), and summer leaves (SL).

The table reports the statistical output of the ANOVA done on the PC (Treatments: CK=unfertilized control, MIN=mineral fertilization, COM=compost) with the significant differences ( $P < 0.05$ )

evident between macronutrient content in the autumn leaves (bottom-right side of the plot) and in the fruit at harvest and roots (upper-right side of the plot).

In the first 0.15 m of soil, the addition of compost increased CEC, EC, Ca, K, Mg, and S compared with control and mineral fertilization (Fig. 3). With the

exception of CEC and Ca, the positive effect of compost was observed also in other soil layers (Fig. 3) and in particular EC was higher in all soil profiles, while the concentration of K, Mg and S were higher than in the control and mineral fertilization between 0 and 0.45 m of depth. The effect of compost decreased



**Fig. 3** Means of soil cation exchange capacity (CEC), electrical conductivity (EC), and soil calcium (Ca), potassium (K), magnesium (Mg) and sulfur (S) content at four sampling depths (0–0.15, 0.16–0.25, 0.26–0.45, 0.46–0.65 m) for the three fertilization treatments (CK=unfertilized control,

MIN=mineral fertilization, COM=compost). Error bars represent the standard error (based on data on field replicates) and the significant differences ( $P < 0.05$ ) between “Treatment”, “Depth”, and “Treatment\*Depth” interaction are reported

with depth for all the investigated parameters; however, while the concentration of K and Mg decreased constantly with depth, the EC decreased until 0.25 m and then remained steady from 0.26 to 0.65 m, and the concentration of Ca, S and CEC decreased until 0.15 m and then remained steady from 0.16 to 0.65 m (Fig. 3). Unfertilized control and mineral fertilization did not show significant differences in nutrient concentrations and in both treatments only a slightly decreasing trend with depth was observed for K and Mg concentration. In control and mineral fertilization, S concentration was higher in the deepest layer than in the shallowest one (Fig. 3).

## Discussion

Calcium and potassium returned to soil with leaf abscission

In this study and as already observed previously (El-Jendoubi et al. 2013) plants macronutrients were

mainly allocated in autumn leaves and in fruit at harvest. However, while in roots, skeleton, pruned wood, autumn leaves, and summer leaves Ca contents were highest among all the other macronutrients, K was the most important macronutrient in thinned fruit and fruit at harvest. Similarly, El-Jendoubi et al. (2013) showed that each nutrient was characterized by a precise allocation pattern: fruits were the largest sink for K, while Mg and Ca were mainly accumulated in abscised leaves.

The difference between the amount of nutrients in summer leaves (sampled in July) and at natural abscission gives an estimation of the fraction of nutrients remobilized at the end of the vegetative season and stored inside the woody part of the plant. In the present experiment, Ca and K showed higher concentrations in autumn leaves than in those sampled in summer indicating no net remobilization through the season. Similar behavior was reported in almond trees (Muhammad et al. 2015). As a consequence, Ca and K allocated to leaves returned to the soil after abscission and decomposition, thus returning partially

available for root uptake (Baldi et al. 2021b) after mineralization. However, despite what was expected and what was observed in other studies (Dang et al. 2022; do Carmo et al. 2016), in our case, soil Ca and K concentration increased in the surface horizon and in the whole soil profile respectively, only when compost was applied (Ca and K mean content of compost were of  $5.8 \pm 1.0\%$  and  $1.5 \pm 0.2\%$ , respectively), and not in control and mineral fertilized plots, meaning that the source of additional Ca was the organic fertilizer rather than the litter formed by abscised leaves. The fact that abscised leaves and/or mineral fertilizer have no such effect on soil Ca content was probably in relation to the natural soil's high abundance in total and active carbonate content (Baldi et al. 2018), indicating a large soil endowment in carbonates thus making it impossible to observe variation in soil Ca content even in the long term.

#### Compost contributed to soil and plants K and Mg content

Differently from Ca, both mineral fertilizer and compost increased K and Mg content in fruits at harvest (Table 2). This effect was also observed by Delian et al. (2012), who reported a higher concentration of potassium than magnesium in nectarine fruits at harvest. Potassium is involved in many physiological and biochemical processes related to plant growth, crop quality, and plant response to stress factors (Delian et al. 2012; Wang et al. 2018). An excess in available potassium is known to induce a Mg deficiency in the plant due to the unidirectional competition for uptake (Xie et al. 2021). In our study, independently from the fertilization treatment (mineral or organic), the lowest K/Mg ratio (approx. 1.8) was measured in plant roots with respect to the other plant organs, indicating that the increase in K concentration in plant organs did not inhibit plants' efficiency to uptake Mg (Xie et al. 2021). The apparently similar plant uptake of K and Mg is confirmed also by the content of these elements in soil samples at the end of the commercial orchard life-time. Indeed, soil samples were not depleted in K nor Mg with values that ranged between 150–400 mg kg<sub>DW</sub><sup>-1</sup>, considering that optimum soil concentrations lie between 240 and 300 mg kg<sub>DW</sub><sup>-1</sup> for K (Xie et al. 2021) and between 25 and 180 mg kg<sub>DW</sub><sup>-1</sup> for Mg (Fox and Piekielek 1984). Moreover, at the end of the experiment,

significantly higher values of both K and Mg content were measured with compost fertilization treatment (compost Mg mean concentration was  $0.43 \pm 0.07\%$ ); this may indicate a greater contribution of compost to soil nutrient content with respect to the mineral fertilization treatments. Similar results were also observed in previous studies (Acharya et al. 2019; do Carmo et al. 2016).

#### Sulfur content had a different trend with compost and mineral fertilization

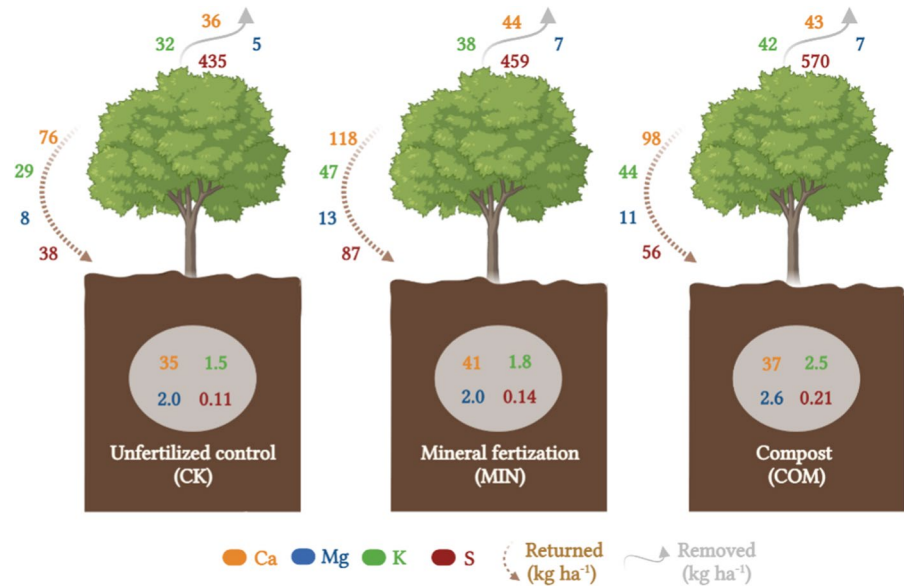
Mineral and compost fertilization enhanced S content in fruit at harvest and in summer leaves more than in autumn leaves. At the end of the nectarine orchard commercial life-time, S content in roots was still high with both treatments indicating a potential availability for bud break in the next vegetative season. Plant production of secondary metabolites is supported by soil S content which resulted particularly high in correspondence of compost treatment. Compost increases soil organic matter, the largest reservoir of S (in organic form) in soil, and compost (in our study characterized by a  $0.18 \pm 0.04\%$  of S mean content) or soil organic matter decomposition could result in organic sulfur mineralization into the  $\text{SO}_4^{2-}$ , which is available to plants (do Carmo et al. 2016; Narayan et al. 2022). Soil sulfur content decreased with depth in the plots treated with compost, while it slightly increased or did not change with depth in the control and mineral fertilized plots. This different trend could be ascribed to the different S forms present in the soil: the organic one related to compost, and thus mainly present in the upper soil layers; and the inorganic one, which moves deeper in the soil profile, and is probably less available to plants and more subjected to leaching and/or co-precipitation as calcium, magnesium or sodium sulfate (Scherer 2001).

#### Compost increased soil CEC and EC

Compost contributes to the increase of exchangeable cations (i.e.  $\text{Ca}^{2+}$ ,  $\text{K}^+$ , and  $\text{Mg}^{2+}$ ) creating favorable conditions for cation exchange (Acharya et al. 2019; Dang et al. 2022). Fourteen years of compost addition significantly increased soil CEC and EC not only in the first (0–0.15 m) but also in the deeper soil layers. Changes in the CEC of soils are directly linked to the negative charges in the SOM and in the humified



**Fig. 4** Macronutrient dynamics in the soil–plant system. Ca, K, Mg, and S content removed from the plant (solid grey arrow) and recycled from plant to soil (dashed brown arrow) are expressed in  $\text{kg ha}^{-1}$ , while total Ca, K, Mg, and S content in soil is expressed in  $\text{Mg ha}^{-1}$



compounds (do Carmo et al. 2016) and to the colloidal nature of organic matter (Kumar Bhatt et al. 2019). Similarly, soil EC increase can be explained by the inputs of nutrients and salts contained in the compost and by the soil organic matter mineralization rate. Notwithstanding, the increase in soil EC values needs to be considered carefully, since above a critical range of  $750\text{--}3490 \mu\text{S cm}^{-1}$  plant growth could be damaged (do Carmo et al. 2016).

## Conclusion

Considering the goals of this study we found that: (1) long-term compost addition facilitates macronutrients storage in the soil and this is functional both for the current crops and for future ones (Fig. 4); (2) the supply of compost, besides maintaining soil quality and fertility, also meets plant nutrient demand thus leading to higher plant performances and to economic and environmental benefits; (3) the synchronization between plant needs and nutrient soil availability is fundamental for a correct fertilization management since it avoids plants' nutritional imbalance and, at the same time, reduces the risk of nutrient leaching. The use of compost makes it difficult to guarantee the mentioned synchronization, but significantly contributes to soil nutrient content and soil quality increase. The exclusive use of mineral fertilizer, if not carefully managed, even

if meeting the plant's nutrient demand, could lead to macronutrient depletion due to scarce reserve creation in the soil; on the other hand, mineral fertilizer represents a source of nutrients readily available to plant uptake. Therefore, the choice of the fertilizer to be used needs to be calibrated on soil and plant requirements taking into account their potential effects (either positive or negative, i.e. the increase of soil organic matter content or the increase of nutrient leaching) on the environment.

Future studies should take into consideration the effects of other organic amendments not only in relation to soil and plant nutrient availability, but also on the effects that compost decomposition could have on the amount of  $\text{CO}_2$  emitted or sequestered by the orchard, and the impact of macronutrient dynamics on soil microbial communities structure and activity.

**Acknowledgements** We would like to thank Dr. Andrea Simoni and Dr. Giampaolo Di Biase for performing the ICP-AES measurements. This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

**Authors contribution** Conceptualization: EB, MT; Methodology: EB; Formal analysis and investigation: EB, MM,

MQ, LC; Writing—original draft preparation: MM; Writing—review and editing: MM, EB, LC; Resources: MT, CM; Supervision: MT, CM.

## Declarations

**Competing interests** The authors declare no competing interests.

## References

- Acharya P, Ghimire R, Cho Y (2019) Linking soil health to sustainable crop production: dairy compost effects on soil properties and sorghum biomass. *Sustain* 11:1–13. <https://doi.org/10.3390/su11133552>
- Adujna G (2016) A review on impact of compost on soil properties, water use and crop productivity. *Agric Sci Res J* 4:93–104. <https://doi.org/10.14662/ARJASR2016.010>
- Baldi E, Cavani L, Margon A, Quartieri M, Sorrenti G, Marzadori C, Toselli M (2018) Effect of compost application on the dynamics of carbon in a nectarine orchard ecosystem. *Sci Total Environ* 637–638:918–925. <https://doi.org/10.1016/j.scitotenv.2018.05.093>
- Baldi E, Cavani L, Mazzon M, Marzadori C, Quartieri M, Toselli M (2021a) Fourteen years of compost application in a commercial nectarine orchard: effect on microelements and potential harmful elements in soil and plants. *Sci Total Environ* 752:141894. <https://doi.org/10.1016/j.scitotenv.2020.141894>
- Baldi E, Quartieri M, Sorrenti G, Toselli M (2021b) Evaluation of nutrients removed and recycled in a commercial peach orchard over a 14-years-production cycle. *Italus Hortus* 28:1–12
- Barreto CF, Antunes LEC, Toselli M, Baldi E, Sorrenti G, Quartieri M (2021) Organic fertilization and crop load in yield and quality of organic nectarines in Italy. *Rev Bras Frutic* 43:3. <https://doi.org/10.1590/0100-29452021016>
- Chatzistathis T, Papadakis IE, Papaioannou A, Chatzissavvidis C, Giannakoula A (2020) Comparative study effects between manure application and a controlled-release fertilizer on the growth, nutrient uptake, photosystem II activity and photosynthetic rate of *Olea europaea* L. (cv. 'Koroneiki'). *Sci Hortic (amsterdam)* 264:109176. <https://doi.org/10.1016/j.scienta.2020.109176>
- Cruz AF, de Almeida GM, Salvador Wadt PG, de Carvalho PM, Gerosa Ramos ML (2019) Seasonal variation of plant mineral nutrition in fruit trees. *Brazilian Arch Biol Technol.* <https://doi.org/10.1590/1678-4324-2019180340>
- de Carmo DL, do Lima LB, Silva CA (2016) Soil fertility and electrical conductivity affected by organic waste rates and nutrient inputs davi lopes. *Rev Bras Cienc Do Solo* 40:1–17. <https://doi.org/10.1590/18069657rbc20150152>
- Delian E, Chira L, Dumitru L, Badulescu L, Chira A, Petcuci A (2012) Mineral content of nectarines fruits in relation to some fertilization practices. *Horticulture LVI* 73–80
- El-Jendoubi H, Abadía J, Abadía A (2013) Assessment of nutrient removal in bearing peach trees (*Prunus persica* L. batsch) based on whole tree analysis. *Plant Soil* 369:421–437. <https://doi.org/10.1007/s11104-012-1556-1>
- FAO (2017) The future of food and agriculture-Trends and challenges
- Fawzi MIF, Shahin FM, Elham AD, Kandil EA (2010) Effect of organic and biofertilizers and magnesium sulphate on growth yield, chemical composition and fruit quality of “Le-Conte” pear trees. *Nat Sci* 8:1–7
- Fox RH, Piekielek WP (1984) Soil magnesium level, corn (*Zea mays* L.) yield, and magnesium uptake. *Commun Soil Sci Plant Anal* 15:109–123
- Kingston HM, Jassie LB (1988) Journal of Research of the National Bureau of Standards Accuracy in Trace Analysis Microwave Acid Sample Decomposition for Elemental. *Analysis* 93:1–6
- Kumar Bhatt M, Labanya R, Joshi HC (2019) Influence of long-term chemical fertilizers and organic manures on soil fertility - a review. *Univers J Agric Res* 7:177–188. <https://doi.org/10.13189/ujar.2019.070502>
- Maity A, Babu KD, Sarkar A (2019) Guidelines for fertilizer use in pomegranate orchards based on seasonal uptake and partitioning of nutrients. *Sci Hortic (amsterdam)* 252:138–148. <https://doi.org/10.1016/j.scienta.2019.03.047>
- Mazzon M, Cavani L, Margon A, Sorrenti G, Ciavatta C, Marzadori C (2018) Changes in soil phenol oxidase activities due to long-term application of compost and mineral N in a walnut orchard. *Geoderma*. <https://doi.org/10.1016/j.geoderma.2017.12.009>
- Muhammad S, Sanden BL, Lampinen BD, Saa S, Siddiqui MI, Smart DR, Olivos A, Shackel KA, DeJong T, Brown PH (2015) Seasonal changes in nutrient content and concentrations in a mature deciduous tree species: Studies in almond (*Prunus dulcis* (Mill.) D. A. Webb). *Eur J Agron* 65:52–68. <https://doi.org/10.1016/j.eja.2015.01.004>
- Narayan OP, Kumar P, Yadav B, Dua M, Johri AK (2022) Sulphur nutrition and its role in plant growth and development. *Plant Signal Behav.* <https://doi.org/10.1080/15592324.2022.2030082>
- R Core Team (2021) R: A language and environment for statistical computing
- Safaei Khorram M, Zhang G, Fatemi A, Kiefer R, Maddah K, Baqar M, Zakaria MP, Li G (2019) Impact of biochar and compost amendment on soil quality, growth and yield of a replanted apple orchard in a 4-year field study. *J Sci Food Agric* 99:1862–1869. <https://doi.org/10.1002/jsfa.9380>
- Scherer HW (2001) Sulphur in crop production-Invited paper. *Eur J Agron* 14:81–111. [https://doi.org/10.1016/S1161-0301\(00\)00082-4](https://doi.org/10.1016/S1161-0301(00)00082-4)
- Sciubba L, Cavani L, Grigatti M, Ciavatta C, Marzadori C (2015) Relationships between stability, maturity, water-extractable organic matter of municipal sewage sludge composts and soil functionality. *Environ Sci Pollut Res* 22:13393–13403. <https://doi.org/10.1007/s11356-015-4611-7>
- Shiwakoti S, Zheljzkov VD, Gollany HT, Kleber M, Xing B, Astatkie T (2020) Macronutrient in soils and wheat from long-term agroexperiments reflects variations in residue and fertilizer inputs. *Sci Rep* 10:1–9. <https://doi.org/10.1038/s41598-020-60164-6>

- Sumner ME, Miller WP (1996) Cation Exchange Capacity and Exchange Coefficients. In: Sparks D, Page A, Helmke P, Loepfert R, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME (Eds.), *Methods of Soil Analysis* <https://doi.org/10.2136/sssabookser5.3.c40>
- Toselli M, Baldi E, Cavani L, Mazzon M, Quartieri M, Sorrenti G, Marzadori C (2019b) Soil-plant nitrogen pools in nectarine orchard in response to long-term compost application. *Sci Total Environ* 671:10–18. <https://doi.org/10.1016/j.scitotenv.2019.03.241>
- Toselli M, Baldi E, Cavani L, Sorrenti G (2019a) Nutrient management in fruit crops: An organic way. In: *Fruit Crops: Diagnosis and Management of Nutrient Constraints*. Elsevier Inc, pp. 379–392 doi: <https://doi.org/10.1016/B978-0-12-818732-6.00027-7>
- Van DL, Ngoc NP, Hung NN (2022) Effects of biochar, lime, and compost applications on soil physicochemical properties and yield of pomelo (*Citrus grandis* Osbeck) in alluvial soil of the Mekong Delta. *Appl Environ Soil Sci*. <https://doi.org/10.1155/2022/5747699>
- Wang X, Hao L, Zhu B, Jiang Z (2018) Plant calcium signaling in response to potassium deficiency. *Int J Mol Sci* 19:1–16. <https://doi.org/10.3390/ijms19113456>
- Xie K, Cakmak I, Wang S, Zhang F, Guo S (2021) Synergistic and antagonistic interactions between potassium and magnesium in higher plants. *Crop J* 9:249–256. <https://doi.org/10.1016/j.cj.2020.10.005>
- Zhang Y, Wang X, Liu B, Liu Q, Zheng H, You X, Sun K, Luo X, Li F (2020) Comparative study of individual and co-application of biochar and wood vinegar on blueberry fruit yield and nutritional quality. *Chemosphere* 246:125699. <https://doi.org/10.1016/j.chemosphere.2019.125699>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.