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

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1 ~~The fate of generally unconsidered macronutrients in plant and soil: effect of different~~
2 ~~fertilization strategy on K, Ca, Mg and S~~

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

4

5

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11

12 **Abstract**

13 Adequate plant nutritional status and soil fertility preservation ~~should~~ can be achieved through ~~the~~
14 ~~employment of~~ sustainable agricultural management techniques. The challenge of intensive orchard
15 cultivation, besides the risk of nutrient decline, is ~~the to prevention of~~ the loss of soil fertility that
16 could lead to soil degradation with a consequent negative impact on yield and fruit quality. The use
17 of organic amendments could be a sustainable strategy to combine ~~elevated~~ high plant performance
18 with soil fertility improvement.

19 This work aims at shedding light on the effects of compost addition with respect to an unfertilized
20 control and a mineral fertilization treatment on macronutrient (K, Ca, Mg, and S) dynamics in plants
21 and soil of a commercial nectarine orchard planted in 2001. ~~Therefore, the manuscript aims at~~
22 ~~shedding light on macronutrient (K, Ca, Mg and S) dynamics in plants and soil of a commercial~~
23 ~~nectarine orchard planted in 2001 and in which three fertilization treatments were compared:~~
24 ~~unfertilized control, mineral fertilization, and compost.~~

25 In the first 0.15 m of soil, compost addition resulted in higher values (26 - 42%) of all the parameters.

26 Both fertilization treatments induced a 28% increase ~~of~~ in roots' S content compared to the control
27 but did not induce macronutrients content variation in plant skeleton, pruned wood, and thinned
28 fruits. In autumn leaves, all the macronutrients resulted in higher values (24 - 45%) with both mineral
29 and compost fertilization, and the same was observed in fruit at harvest (increases of 15 - 31%).

30 ~~Finally, in the first 0.15 m of soil, compost addition resulted with the higher values (+ 26 - 42%) of all~~
31 ~~the parameters.~~

32 In our study, the treatment with compost satisfied plants' nutrient demands as much as the mineral
33 fertilizer. In addition, compost treatment also improved soil nutrient content while preserving yield.

34 Our results show that it is possible to reconcile plant nutrient needs with the preservation of soil
35 fertility with the aim of reaching agriculture sustainability.

36 ~~Thus, the long term use of mineral fertilizer, even if meeting plant's nutrient demand, could lead to~~
37 ~~soil macronutrient depletion. Whereas, organic amendments addition could not only satisfy plant's~~
38 ~~nutrient demand but also maintain soil quality and fertility through the higher macronutrients~~
39 ~~storage in the soil; this would lead to both higher plant performances and to economic and~~
40 ~~environmental benefits.~~

41

42 **Keywords**

43 *Prunus persica*, soil nutrient availability, compost, mineral fertilization, nutrient removal, soil
44 macronutrient content.

45 1. Introduction

46 The ~~rising-increasing~~ demand for high-quality nutritional food related to ~~the constant-steady~~
47 increase ~~of-in~~ population (El-Jendoubi et al., 2013) is leading to the necessity to ~~maximise-maximize~~
48 yield ~~by-while~~ minimizing ecosystem impacts deriving from agriculture. According to the report of
49 the Food and Agriculture Organization of the United Nations (FAO, 2017), the requirements for
50 adequate food supplies have to pass through sustainable agricultural management techniques. This
51 issue also deals with adequate plant nutritional status and preservation/increase of soil fertility
52 (Toselli et al., 2019a; Zhang et al., 2020). Plant nutrition ~~depends on is the result of~~ the nutrient cycle
53 in and out of the orchard ecosystem. The inputs to the soil, for example, include mineral and/or
54 organic fertilizers, atmospheric deposition, and biological nitrogen (N) fixation, while the outputs
55 are represented by harvested fruits, nutrients lost by leaching, gaseous losses, and erosion (Toselli
56 et al., 2019b). In case of a negative balance between inputs and outputs, the soil would come across
57 a nutrient depletion that, in the long-term, would lead to an unsustainable farming system (El-
58 Jendoubi et al., 2013). The challenge of intensive orchard cultivation is, besides the risk of nutrient
59 decline, the loss of soil fertility (both chemical and biological) that could lead to soil degradation (i.e.
60 loss of soil organic matter, erosion, acidification, and pollution) with a consequent negative impact
61 on plant performances (Zhang et al., 2020). Thus, the great challenge for modern farmers is to
62 maintain and/or increase soil fertility in a sustainable way. This could be reached through the
63 application of organic amendments (i.e. composts, biochar, and manures) that are widely ~~recognised~~
64 ~~recognized~~ to be ~~cheapinexpensive~~, to ~~release slowly release the~~ nutrients through mineralization
65 ~~slowly~~, and to enhance soil carbon (C) and organic matter increase (Mazzon et al., 2018; Sciubba et
66 al., 2015) thus stimulating carbon dioxide sequestration. In addition, the application of organic
67 matter ~~is able to can~~ improve soil physical properties (Chatzistathis et al., 2020) as, for example, bulk
68 density reduction and aggregate stability and water holding capacity increase (Adugna, 2016),

69 positively affecting soil microbial community (Fawzi et al., 2010; Safaei Khorram et al., 2019) and
70 increasing macro- and micro-nutrient availability (Baldi et al., 2021a; Fawzi et al., 2010). Organic
71 amendments thus represent not only a source of N, phosphorus (P), and potassium (K) but also of
72 calcium (Ca), magnesium (Mg), and sulphur (S) ~~that-which~~ are equally considered ~~as~~-essential plant
73 macronutrients (Barreto et al., 2021; Shiwakoti et al., 2020). In the study of Shiwakoti et al. (2020),
74 ~~the-farmyard-manure~~ long-term (approximately 64 years) addition ~~of farmyard manure~~ (at the
75 rate of 11.2 Mg ha⁻¹ year⁻¹) evidenced higher macronutrient (K, S, and Mg) content in soil than the
76 other treatments (pea vine and wheat residues, with and without N addition) mainly due to the high
77 amounts of these nutrients that directly contribute to soil chemical fertility. Shiwakoti et al. (2020)
78 also highlighted that manure could have activated soil cation exchange sites releasing organic
79 colloids and consequently adsorbing K to the exchangeable sites and increasing its availability.
80 Macronutrient soil availability throughout the growing season is fundamental for fruit trees. In a
81 study on pomegranate nutrient dynamics, Maity et al. (2019) demonstrated that ~~most of~~ plant needs
82 were ~~mostly~~ satisfied by uptake from ~~the~~ soil more than ~~from the~~ mobilization from plant reserves;
83 as a consequence, if soil nutrients are not replenished through appropriate fertilization management,
84 fruit yield and quality could be severely impaired. In a different study on various fruit trees (i.e.
85 apple, peach, and mandarin), Cruz et al. (2019) showed that adequate K supply at fruit set is of
86 fundamental importance for the final fruit quality. Maity et al. (2019) evidenced that a great amount
87 of Mg was remobilized from leaves to fruit at ~~the~~ maturity stage, while S was mainly concentrated
88 in shoots and Ca in ~~the~~ woody organs of pomegranate. El-Jendoubi et al. (2013) found that K, P, and
89 N mainly accumulate in fruits, while Mg and Ca in abscised leaves. Moreover, it is estimated that
90 peach trees in commercial orchards have a macronutrient requirement accounting for 74 - 425 g K
91 tree⁻¹, 25 - 518 g Ca tree⁻¹, and 9 - 74 g Mg tree⁻¹ (Baldi et al., 2021b) every year.

92 The key issue for fruit tree nutrition is the availability of nutrients in the soil during the entire
93 vegetative season, consequently, the use of organic amendments, that gradually release nutrients
94 through mineralization, could be a sustainable strategy able to combine elevated plant performance
95 with the improvement of soil fertility (Baldi et al., 2021b).

96 This manuscript follows ~~3~~-three previous publications on C (Baldi et al., 2018), N (Toselli et al.,
97 2019b), and micronutrients ~~on~~-in the same experiment (Baldi et al., 2021a), and aims at shedding
98 shedding light on ~~other nutrients such as~~ the macronutrients K, Ca, Mg, and S. Indeed, the goal of the
99 present study was to determine the effects of the long term mineral fertilization and compost
100 addition in ~~the long term~~ nectarine orchard (14 years) on: i) soil macronutrient content at the end
101 of the 14-years life-time of the ~~nectarine~~ orchard, ii) macronutrient content in different plant organs,
102 and iii) the relation between plant and soil macronutrient content.

103

104 2. Materials and methods

105 2.1 Orchard description and treatments

106 The experiment was carried out on a commercial nectarine orchard [*Prunus persica*, Batsch var.
107 *nucipersica* (Bockh.) Schn.] planted in 2001 (Table 1). The orchard was located in the Po valley (Italy)
108 near Ravenna (44°27' N;12°13' E), an area characterized by a temperate climate and a silt-loam soil
109 (Calcaric Cambisol) with a total carbonate content (% CaCO₃) of 31 ± 1 and an active carbonate
110 content (% CaCO₃) of 13 ± 1 (Baldi et al., 2021a, 2018). The pPlanting layout and main orchard
111 management strategies are reported in Table 1. Since orchard plantation, three fertilization
112 treatments were compared with four replicates (4 trees each) according to a complete randomized
113 block design: unfertilized control (CK); mineral fertilization (MIN); and compost (COM). Specific
114 information regarding the treatments ~~are~~-is reported in Table 1. Fertilizers were applied ~~on~~-to the

115 tree row and tilled into the soil to a depth of 0.25 m, while pruned wood was left into the ground
116 and chopped (Baldi et al., 2021a, 2018; Toselli et al., 2019b).

117

118 **Table 1** – Nectarine orchard main characteristics and management strategies (Baldi et al., 2021a, 2018; Toselli
119 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>	Done a According to Crop Management Guideline of the region Emilia-Romagna (www.regione.emilia-romagna.it).
<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 ⁻¹ yr ⁻¹ (60% in May and 40% in September); in 2004, N rate was increased to 120 kg ha ⁻¹ yr ⁻¹ and from 2006 to 130 kg ha ⁻¹ yr ⁻¹ . <u>Nitrogen was applied as ammonium nitrate (N = 35%), while P and K were applied as a binary fertilizer (P = 10%; K = 20%); no micronutrients was provided in mineral fertilization.</u> Phosphorus (P) at 100 and potassium (K) at 200 kg ha ⁻¹ (applied only at planting). Rate established according to Integrated Crop Management Guideline of the region Emilia-Romagna (www.regione.emilia-romagna.it). <u>Nitrogen was applied as ammonium nitrate (N = 35%), while P and K were applied as a binary fertilizer (P = 10%; K = 20%); no micronutrients was provided with mineral fertilization.</u>

Compost (COM)

Applied at a rate of 10 t DW ha⁻¹ yr⁻¹, equal to 240 kg N ha⁻¹ yr⁻¹.

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⁻¹, C/N ratio 10.2, and (in g kg_{DW}⁻¹) organic C 234, N 21.1, P 4.8, K 15.2.

120

121 2.2 Plant sampling and analysis

122 In 2014, after 14 years of life, 4 trees per treatment were harvested and divided into organs ~~as~~
123 described by Baldi et al. (2021a, 2018) and Toselli et al. (2019b). Briefly, thinned fruits were collected
124 in spring and weighed, and a representative sample was ~~then~~ oven-dried and milled (2 mm). In
125 July, a sample of 40 young fully expanded leaves was collected from the apical part of shoots, and
126 the leaf area was measured by a portable area meter (Li-3000, LiCor inc., Lincoln, Nebraska). Leaves
127 were then washed, oven-dried, and milled at 2 mm. At harvest, in August, plant yield was recorded;
128 afterwards, ~~on a representative sample of fruits~~, fresh weight (FW) and dry weight (DW) of flesh
129 and kernel were measured on a representative sample of fruits; dried flesh and kernel were weighed
130 and milled. In September, one tree per plot was enclosed into a plastic net to collect autumn leaves
131 that were weighed, leaf area measured, dried, and milled. In December 2014, at the end of the
132 commercial life of the orchard, the same trees were harvested, divided into roots, trunks, branches
133 (age > 2 years), and current year shoots (twigs), and weighed. A subsample of each organ was oven-
134 dried, weighed, and milled. ~~The sample of r~~Roots ~~was~~ were washed with deionized water to
135 remove soil residues.

136 A sample (0.3 g) of each plant organ was mineralized according to the US EPA Method 3052
137 (Kingston and Jassie, 1988) in an Ethos TC microwave (Milestone, Bergamo, Italy), filtered
138 (Whatman 42®), and analyzed for Ca, K, Mg, and S by ~~Inductively-inductively Coupled-coupled~~

139 ~~Plasma-plasma Optical-optical Emission-emission Spectrometer-spectrometer~~ (ICP-OES; Ametek
140 Spectro, Arcos, Kleve, Germany). Blank and certified reference materials (NIST standard reference
141 material SRM 1573a tomato leaves and SRM 1570a spinach leaves) analyses were performed.

142 Relative uncertainty, calculated as the relative deviation of the measured element concentration to
143 its certified value, was typically better than $\pm 5\%$.

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

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

151

152 2.3 Soil sampling and analysis

153 In December 2014, an 80 cm deep soil core (70 mm diameter) was collected in the row of each plot
154 with a soil column cylinder auger that was inserted into the soil using a tractor. The core was
155 carefully removed from the auger and divided into four parts according to depth: 0 - 0.15 m, 0.16 -
156 0.25 m, 0.26 - 0.45 m and 0.46 - 0.65 m. Soil from each depth was separately weighted and oven dried
157 at 105°C for 24 hours to evaluate soil bulk density (BD) ~~that-which~~ was calculated as the ratio
158 between DW and the volume of each core. In addition, soil samples were collected, always in the
159 row, with an auger at 0-0.15 m, 0.16-0.25 m, 0.26-0.45 m, and 0.46-0.65 m ~~of~~ depth. Each sample
160 (made of 4 sub-samples) was sieved (2 mm), cleaned from roots and visible plant residues, and air-
161 dried or stored at 4°C. A ~~sub-sub~~ sample was then used to evaluate soil total concentration of Ca, K,
162 Mg, and S. Briefly, samples were subjected to wet mineralization by treating 0.5 g of dry sample

163 with 6 mL of hydrochloric acid (37%), 2 mL of nitric acid (65%) and 2 mL of hydrogen peroxide
164 (30%) in an Ethos TC microwave lab station (Milestone, Bergamo, Italy) according to the methods
165 ISO 12914:2012 and 22036:2008. Solutions were filtered (Whatman 42®) and the element
166 concentration was determined by plasma spectrometer (ICP-OES; Ametek Spectro, Arcos, Kleve,
167 Germany). Blank and certified reference material (BCR reference material No 141R calcareous loam
168 soil) analyses were performed; relative uncertainty, calculated as the relative deviation of the
169 measured element concentration to its certified value, was typically better than ± 5%. Soil pseudo-
170 total mineral element content at the end of the orchard life-time was calculated by multiplying the
171 nutrient concentration by the soil bulk density at the respective depth intervals. Electrical
172 conductivity (EC) was measured on a suspension of 10 g of fresh sample and 20 mL of deionised
173 water that was stirred for 120 min at 25°C and filtered before measurement. Soil potential cation
174 exchange capacity (CEC) was estimated using the ammonium acetate method (Sumner and Miller,
175 1996).

176

177 2.4 Statistical analysis

178 After assumption verification (Shapiro-Wilk for normality and Bartlett for homogeneity of variance),
179 pPlant organ data were ~~analysed~~analyzed with a one-way ANOVA with treatment as a factor (three
180 levels: unfertilized control, mineral fertilization, and compost) ~~after assumption verification~~
181 ~~(Shapiro Wilk for normality and Bartlett for homogeneity of variance)~~. Whether necessary, data
182 were transformed using the Box-Cox procedure to fit the ANOVA assumption. Similarly, data on
183 macronutrient content for~~of~~ autumn and summer leaves ~~macronutrient content~~ were analysed with
184 a ~~two~~one-way ANOVA with ~~treatment and~~ season as a factors. When significant differences occur
185 ($P \leq 0.05$), an HSD post-hoc test (Tukey's test) was applied to separate the means. A Principal
186 Component Analysis (PCA) was carried out using plant organ data ~~that showed~~ing significant

187 differences ~~for in~~ the treatments~~ss~~. Soil data were ~~analysed-analyzed~~ using a split-plot design, with
 188 treatments (three levels: unfertilized control, mineral fertilization, and compost) as the main factor
 189 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.
 190 ANOVA assumption verification and means separation were ~~done-asperformed as described~~ -for
 191 plant organs (R Core Team, 2021).

192

193 3. Results

194 Fertilization treatments, no matter which one, induced on average a 28% increase ~~of in~~ roots' S
 195 content compared to the control (Table 2). The fertilization treatments did not induce a variation of
 196 Ca, K, Mg, and S content in the plant skeleton, pruned wood, and thinned fruits (Table 2). On the
 197 contrary, all the considered macronutrients ~~considered~~ (Ca, K, Mg, and S) ~~were~~ increased in autumn
 198 leaves (in a range from 24 to 45%) by both mineral and compost fertilizations. Similar results in
 199 ~~correspondence of~~ the two fertilization treatments (with increases between 15 and 31%) ~~was-were~~
 200 observed in fruit at harvest with the exception of Ca content that did not show any differences
 201 among treatments (Table 2).

202

203 **Table 2** – Macronutrient content (g pt⁻¹) in plant organs ± standard error (based on field replicates). Different
 204 lowercase letters indicate significant (P < 0.05) differences between treatments (CK = unfertilized control, MIN
 205 = mineral fertilization, COM = compost).

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 ^b	3.6 ± 0.1 ^b	2.0 ± 0.1 ^b
	MIN	2.4 ± 0.1	51 ± 2 ^{ab}	4.8 ± 0.3 ^a	2.8 ± 0.1 ^a
	COM	2.4 ± 0.2	57 ± 1 ^a	4.8 ± 0.2 ^a	2.8 ± 0.1 ^a
	<i>p.value</i>	0.867	0.010	0.012	0.006
Autumn leaves	CK	118 ± 3 ^b	43 ± 2 ^b	14 ± 0.3 ^b	2.6 ± 0.2 ^b
	MIN	181 ± 23 ^a	70 ± 7 ^a	21 ± 2 ^a	4.7 ± 0.5 ^a
	COM	156 ± 9 ^a	66 ± 4 ^{ab}	19 ± 2 ^a	4.5 ± 0.4 ^a
	<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 ^b
	MIN	21 ± 4	5.2 ± 0.5	3.0 ± 0.5	0.43 ± 0.03 ^a
	COM	24 ± 0.3	6.1 ± 0.7	3.6 ± 0.2	0.45 ± 0.03 ^a
	<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

206

207 No significant differences between fertilization treatments were observed in the concentration of
 208 nutrients in summer leaves (Table 3); the only exception was Mg which resulted in a 13% higher
 209 concentration in the control compared to the two fertilization strategies (Table 3).

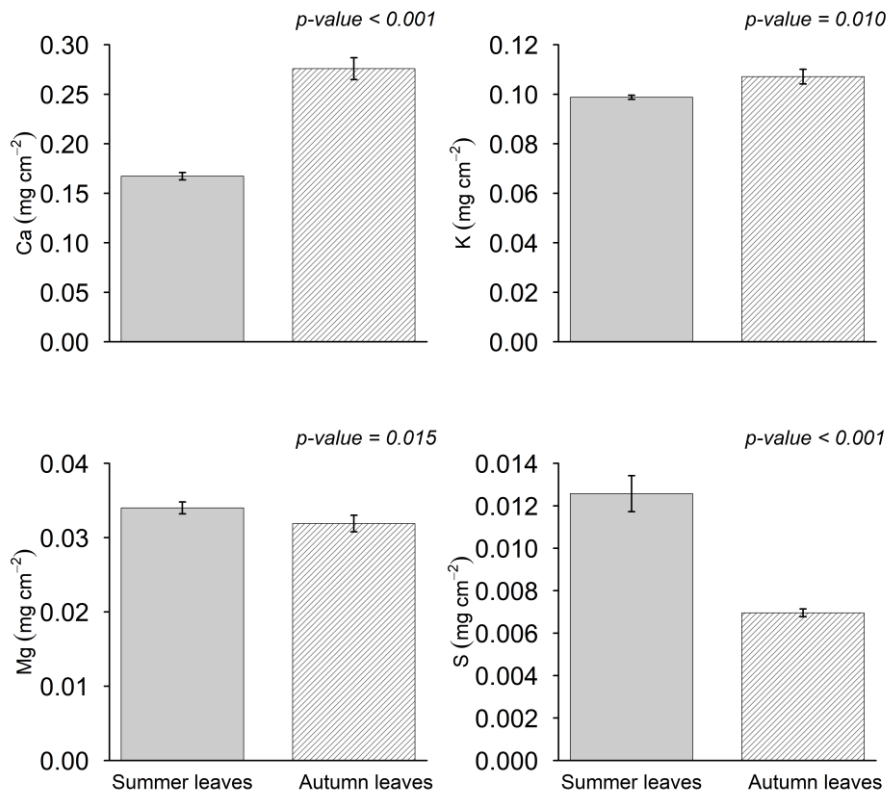
210

211 **Table 3** – Macronutrient concentration (g 100 g⁻¹ DW) ± standard error (based on field replicates) in leaves
 212 sample in summer. Different lowercase letters indicate significant (P < 0.05) differences between treatments
 213 (CK = unfertilized control, MIN = mineral fertilization, COM = compost).

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

214

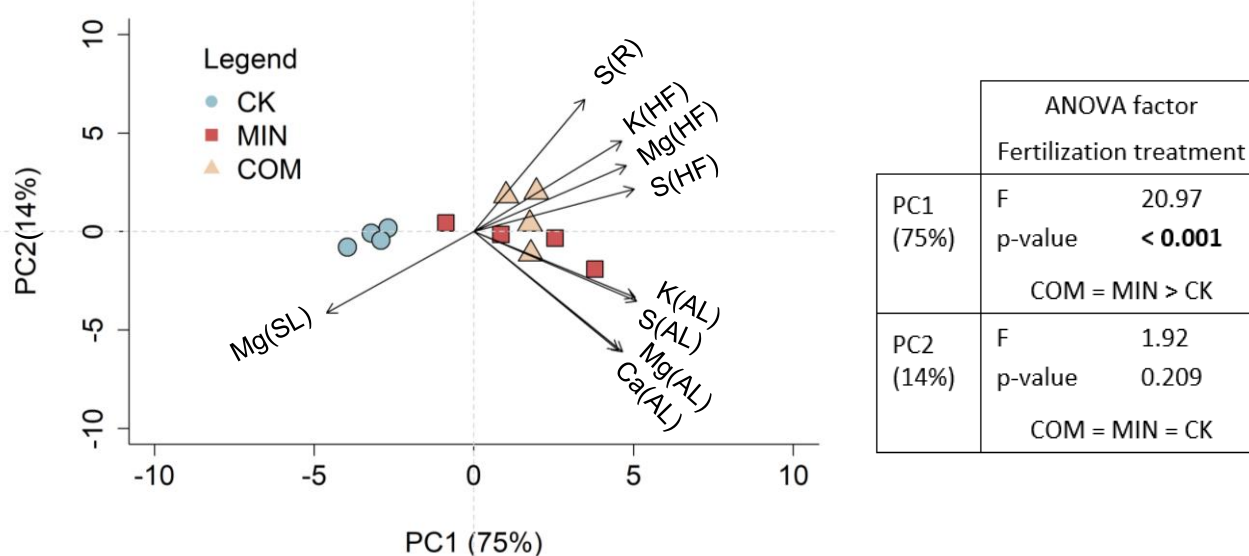
215 The comparison of macronutrients content in autumn and summer leaves highlighted the significant
 216 impact of the season-phenological state for all ~~the~~ four macronutrients considered in this study
 217 (Figure 1). Specifically, higher concentrations of Ca and K were observed in autumn than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



219
 220 **Figure 1**– Means of summer and autumn leaves content of calcium (Ca), potassium (K), magnesium (Mg) and
 221 sulphur (S). Error bar represent the standard error (based on four leaf samples collected in field replicates) and
 222 the significant differences ($P \leq 0.05$) are reported.

223
 224
 225 A PCA (Figure 2) was ~~done performed using with macronutrients content in data from~~ those organs
 226 whose macronutrient content was that were significantly affected by the fertilization treatments
 227 (Table 2). The treatments clusterized were split ~~resulted into~~ two main cluster-groups (according to
 228 PC1 ANOVA results): the unfertilized control in-on the left side of the plot, and the two fertilization
 229 strategies (mineral and compost) in-on the right side of the plot. These two groups showed to be

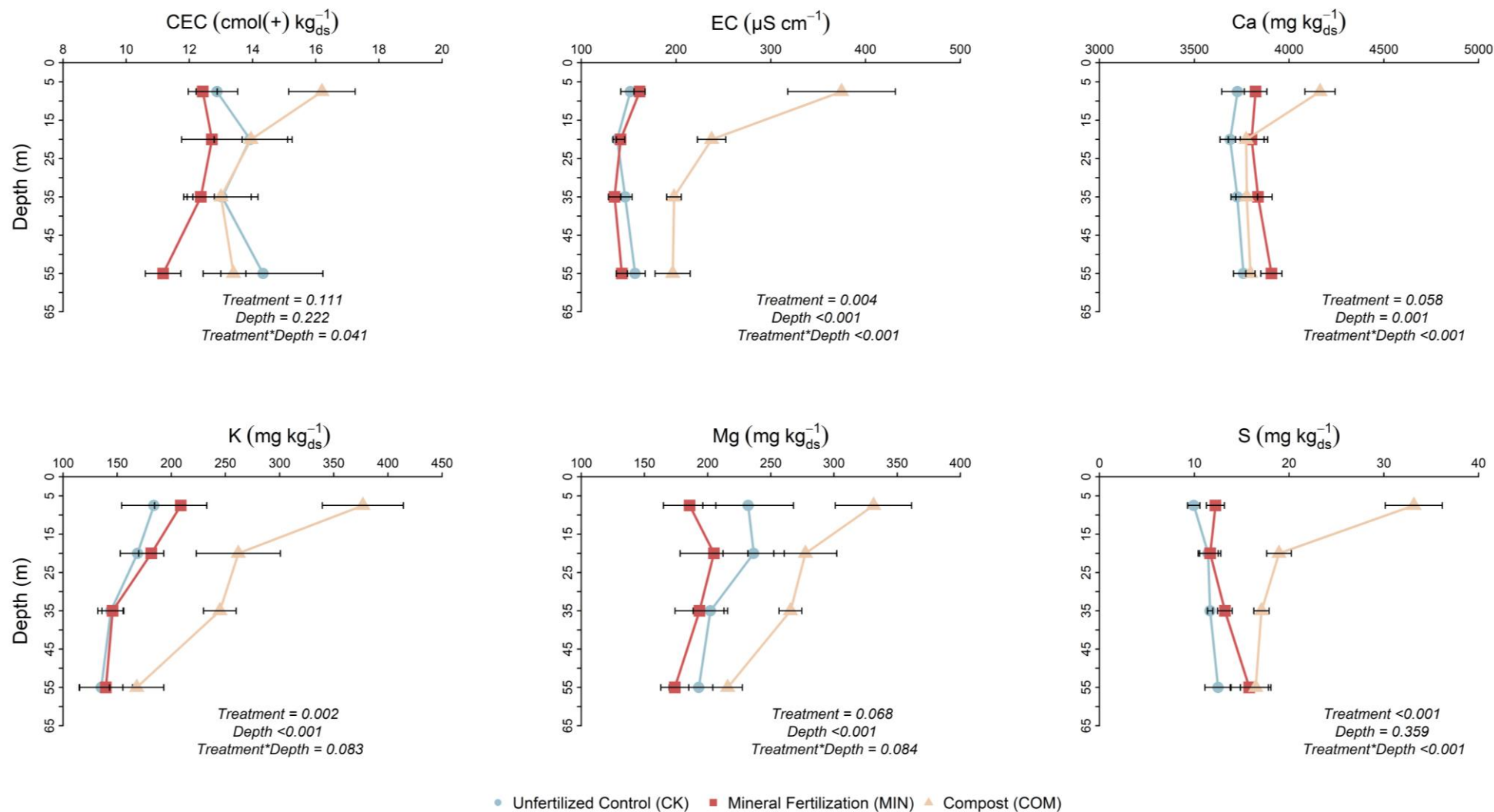
230 clearly defined with-by the Mg content in summer leaves that characterized the unfertilized control
 231 group (Figure 2). A clear separation in plot space was also evident between macronutrients content
 232 in the autumn leaves (bottom-right side of the plot) and in the fruit at harvest and roots (upper-right
 233 side of the plot).



244 **Figure 2**– Principal component (PC) analysis with macronutrients content (calcium (Ca), potassium (K),
 245 magnesium (Mg) and sulfur/sulphur (S)) in the most relevant plant organs: harvested fruits (HF), roots (R),
 246 autumn leaves (AL), and summer leaves (SL). In the table are reported reports the statistical output of the
 247 ANOVA done on the PC (Treatments: CK = unfertilized control, MIN = mineral fertilization, COM = compost)
 248 with t-he significant differences (P < 0.05).

252 In the first 0.15 m of soil, the addition of compost increased CEC, EC, Ca, K, Mg, and S compared
 253 with control and mineral fertilization (Fig. 3). With the exception of CEC and Ca, the positive effect
 254 of compost was observed also in other soil layers (Fig. 3) and in particular EC was higher in all soil

255 profiles, while the concentration of K, Mg and S were higher than in the control and mineral
256 fertilization between 0 and 45 cm of depth. The effect of compost decreased with depth for all the
257 ~~investigated~~ parameters ~~investigated~~; however, while the concentration of K and Mg decreased
258 constantly with depths, the EC decreased until 25 cm and then ~~was~~ remained steady from 26 to 65
259 cm, and the concentration of Ca, S and CEC decreased until 15 cm and then ~~was~~ remained steady
260 from 16 to 65 cm (Fig. 3). Unfertilized control and mineral fertilization did not show significant
261 differences in nutrient concentrations and in both treatments only a slightly decreasing trend with
262 depth was observed for K and Mg concentration. In control and mineral fertilization, S concentration
263 was higher in the deepest layer than in the ~~superficial~~ shallowest one (Fig. 3).



264

265 **Figure 3** – Means of soil cation exchange capacity (CEC), electrical conductivity (EC), and soil calcium (Ca), potassium (K), magnesium (Mg) and sulphur (S) content
 266 at four sampling depth (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
 267 = compost). Error bars represent the standard error (based on data on field replicates) and the significant differences (P ≤ 0.05) between “Treatment”, “Depth”, and
 268 “Treatment*Depth” interaction are reported.

269 4. Discussion

270 ~~In this study and as already observed previously (El-Jendoubi et al., 2013) plants macronutrients~~
271 ~~were mainly allocated in autumn leaves and in fruits at harvest. However, while in roots, skeleton,~~
272 ~~pruned wood, autumn leaves, and summer leaves Ca contents were highest among all the other~~
273 ~~macronutrients, K was the most important macronutrient in thinned fruit and fruit at harvest.~~
274 ~~Similarly, El-Jendoubi et al. (2013) showed that each nutrient was characterized by a precise~~
275 ~~allocation pattern: fruits were the largest sink for K, while Mg and Ca were mainly accumulated in~~
276 ~~abscised leaves.~~

277 4.1 *Calcium and potassium returned to soil with leaf abscission* ~~abundance and allocation~~

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

285 The difference between the amount of nutrients in summer leaves (sampled in summer July) and at
286 natural abscission gives an estimation of the fraction of nutrients remobilized at the end of the
287 vegetative season and stored inside the woody part of the plant. In the present experiment, Ca and
288 K showed higher concentrations in autumn leaves than in those sampled in summer indicating no
289 net remobilization through the season. ~~SA~~ similar behavior was reported in almond trees
290 (Muhammad et al., 2015). As a consequence, Ca and K allocated ~~in autumn to~~ leaves returned ~~into to~~
291 the soil after abscission and ~~degradation decomposition~~, thus ~~becoming again returning~~ partially
292 available for root uptake (Baldi et al., 2021b) after mineralization. ~~On the other hand, little quantities~~

293 ~~of Ca and K reservation are available for spring new growth.~~ However, despite what was expected
294 and what was observed in other ~~study studies~~ (Dang et al., 2022; do Carmo et al., 2016), in ~~this our~~
295 case, soil Ca and K concentration increased in the surface horizon and in the whole soil profile
296 respectively, only when compost was applied (CaO and K mean content of compost ~~was were~~ of
297 ~~8.25.8 ± 1.0 % and 1.5 ± 0.2 %, respectively~~), and not in control and mineral fertilized plots, meaning
298 that the source of additional Ca was the organic fertilizer rather than the litter ~~made of~~ formed by
299 abscised leaves. ~~This The lack of effect~~ fact that abscised leaves and/or mineral fertilizer have no such
300 effect on soil Ca content was probably in relation to the natural soil's high abundance in total and
301 active carbonate content (CaCO₃) (Baldi et al., 2018), indicating a large soil endowment in carbonates
302 thus making it impossible to observe variation in soil Ca content even in the long term.

303

304 4.2 ~~K and Mg in plant and soil~~ Compost contributed to soil and plants K and Mg content

305 Differently from Ca, ~~the fertilization treatments~~ (both mineral fertilizer and compost) ~~induced an~~
306 increased ~~of~~ K and Mg content ~~also~~ in fruits at harvest (Table 2). This effect was also observed by
307 ~~Increase of K content in fruits was observed also in another study on nectarine~~ (Delian et al., (2012),
308 who reported a higher concentration of potassium than magnesium in nectarine fruits at
309 harvest ~~where at harvest macronutrients concentration in fruits followed the order K > Ca > Mg.~~
310 Potassium ~~is not an essential element for organic molecules and it is not considered a structural~~
311 ~~element~~ (Delian et al., 2012); ~~however,~~ it is involved in many physiological and biochemical
312 processes related to plant growth, crop quality, and plant response to stress factors (Delian et al.,
313 2012; Wang et al., 2018). An excess in available P potassium is ~~also~~ known to induce a Mg ~~deficiency~~
314 in the plant due to the unidirectional competition for uptake between K and Mg for which an
315 increase in K concentration reduces Mg uptake (Xie et al., 2021). In ~~this our~~ study, independently
316 from the fertilization treatment (mineral or organic), the ~~lower~~ lowest K/Mg ratio (approx. 1.8) was

317 ~~determined-measured~~ in plant roots with respect to the other plant organs, (approx. 1.8) thus
318 indicating that the increase in K concentration in plant organs did not inhibit plants' efficiency to
319 uptake Mg (Xie et al., 2021) ~~was not limited by the high plant K concentrations~~. The apparently
320 similar plant uptake of K and Mg is confirmed also by the content of these elements in soil samples
321 at the end of the commercial orchard life-time. Indeed, soil samples were not depleted in K nor Mg
322 with values that ranged between 150 – 400 mg kg dw⁻¹, considering that optimum soil concentrations
323 lie between 240 and 300 mg kg dw⁻¹ for K (Xie et al., 2021) and between 25 and 180 mg kg dw⁻¹ for
324 Mg (Fox and Piekielek, 1984). Moreover, at the end of the experiment, significantly higher values of
325 both K and Mg content were measured with compost fertilization treatment (compost ~~K₂O and MgO~~
326 mean concentration was ~~of 1.4 ± 0.2 % and 0.72-43 ± 0.07 % respectively~~); this may indicating indicate
327 a its greater contribution of compost to soil nutrient content with respect to the ~~other-mineral~~
328 fertilization treatments. Similar results ~~for these macronutrients~~ were also observed in previous
329 studies (Acharya et al., 2019; do Carmo et al., 2016) ~~and could be also related to compost chemical~~
330 characteristics.

331

332 4.3 Sulfur/Sulphur content had a different trend with compost and mineral fertilization destiny in plant roots 333 and soil: fertilization treatment effects

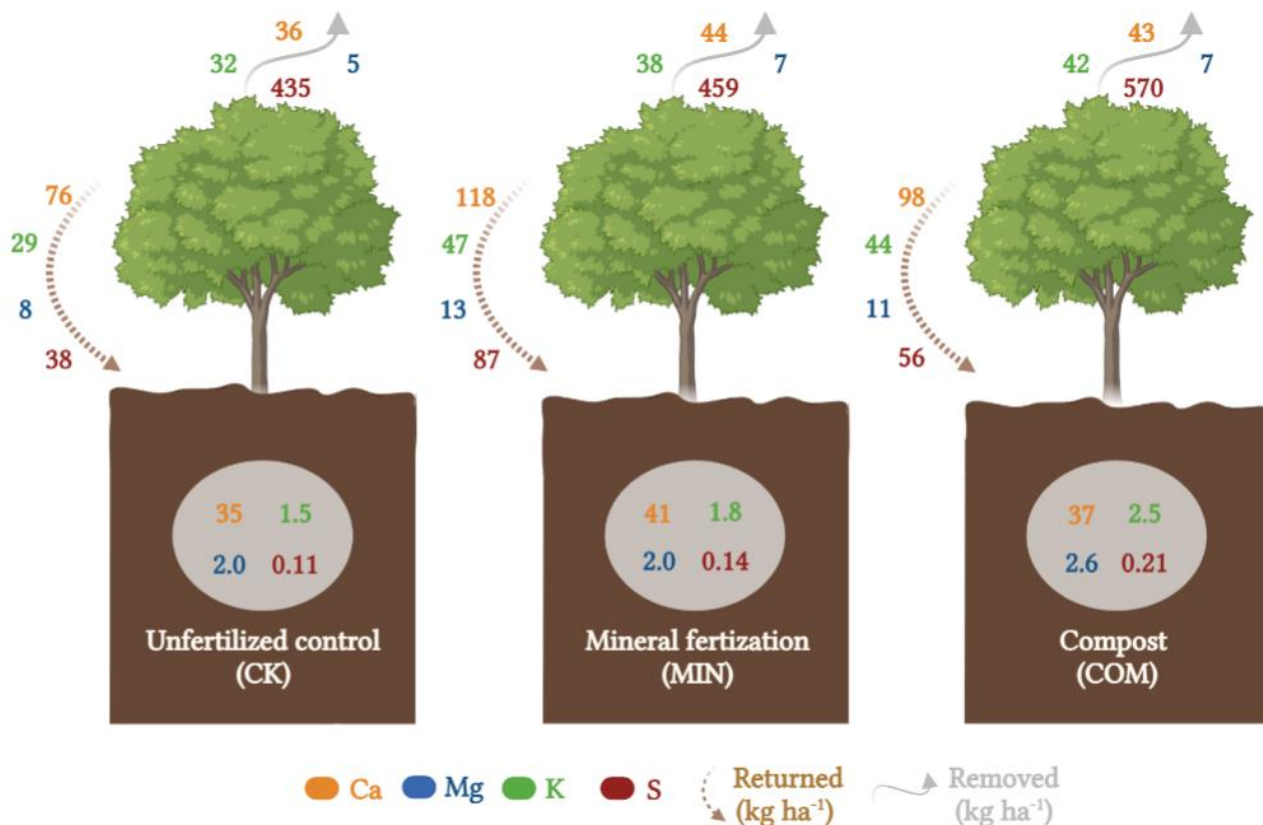
334 Mineral and compost fertilization enhanced S content in fruits s at harvest and in summer leaves more
335 than in autumn leaves. At the end of the nectarine orchard commercial life-time, S content in roots
336 was still high with the twoboth treatments indicating a potential availability for bud sprout break in
337 the next vegetation-vegetative season. ~~Indeed, S is a component of some secondary metabolites used~~
338 for plant's physiological functions and development (Narayan et al., 2022). This pPlant activity
339 production of secondary metabolites is ~~supposed to be~~ supported by soil S content which ~~indeed~~
340 resulted particularly high in correspondence of compost additiontreatment. Compost ~~as an organic~~

341 ~~matter supply increased~~ increases soil organic matter, the largest reservoir of S (in organic form) in ~~to~~
342 soil, ~~and~~ Thus compost (in our study characterized by a ~~0.44-18~~ ± 0.04 % of SO_3 mean content) or soil
343 organic matter decomposition could result in organic sulfur mineralization into the SO_4^{2-} , which is
344 available to plants (do Carmo et al., 2016; Narayan et al., 2022). ~~However, while~~ Soil S-sulfur content
345 decreased with depth in ~~correspondence of the plots treated with~~ compost addition, while it slightly
346 increased or did not change with depth in the control and mineral fertilized plots. This different
347 trend could be ascribed to the different S forms present in the soil: the organic one related to
348 compost, and thus mainly present in the upper soil layers, ~~;~~ and the inorganic one, which accumulate
349 moves deeper in the soil profile, and is probably less available to plants and more subjected to
350 leaching and/or co-precipitation as calcium, magnesium or sodium ~~sulphate-sulfate~~ (Scherer, 2001).

351

352 4.4 Compost ~~effects on soil chemistry~~ increased soil CEC and EC

353 Compost contributes to the increase of exchangeable cations (i.e. Ca^{2+} , K^+ , and Mg^{2+}) creating
354 favorable conditions for cation exchange (Acharya et al., 2019; Dang et al., 2022). Fourteen years of
355 compost addition significantly increased soil CEC and EC not only in the first (0 - 0.15 m) but also
356 in the deeper soil layers. Changes in the CEC of soils are directly linked to the negative charges in
357 the SOM and in the humified compounds (do Carmo et al., 2016) and to the colloidal nature of
358 organic matter (Kumar Bhatt et al., 2019). Similarly, soil EC increase can be explained by the inputs
359 of nutrients and salts contained in the compost and by the soil organic matter mineralization rate.
360 Notwithstanding, the increase ~~of in~~ soil EC values needs to be considered carefully, since ~~-~~ above a
361 critical range of 750 - 3490 $\mu\text{S cm}^{-1}$ plant growth could be damaged (do Carmo et al., 2016).



362

363 **Figure 4** - Macronutrient dynamics in the soil-plant system. Ca, K, Mg and S content removed from
 364 the plant (solid grey arrow) and recycled from plant to soil (dashed brown arrow) are expressed in
 365 kg ha⁻¹, while Ca, content in soil is expressed in g over kg dry weight and K, Mg, and S soil content
 366 in soil are is expressed in mg over kg dry weight Mg ha⁻¹.

367

368 5. Conclusion

369 Considering the goals of this study we have found that: (i) Longlong-term compost addition
 370 facilitates macronutrients storage in the soil and thus indicating that it would favour soil
 371 macronutrients availability for the next crops (Figure 4). Moreover, organic amendment addition,
 372 not only maintain this is functional both for the current crops and for future ones (Fig. 4); (ii) The
 373 supply of compost addition, besides maintaining soil quality and fertility, but also meets plant's
 374 nutrient demand thus leading to higher plant performances and to economic and environmental
 375 benefits.; (iii) The synchronization between plant needs and nutrient soil availability is
 376 fundamental for a correct fertilization management since it avoid plants' nutritional imbalance and,

377 at the same time, reduce the risk of nutrient leaching. The use of compost makes it difficult to
378 guarantee the mentioned synchronization, but significantly contributes to soil nutrient content and
379 soil quality increase. ~~On the other hand,~~ The exclusive use of mineral fertilizer, if not carefully
380 managed, even if meeting the plant's nutrient demand, could lead to macronutrient depletion due
381 to scarce reserve creation in the soil; on the other hand, mineral fertilizer represents a source of
382 nutrients readily available to plant uptake. Therefore, the choice of the fertilizer to be used needs to
383 be calibrated on soil and plant requirements taking into account their potential effects (either
384 positive or negative, i.e. the increase of soil organic matter content or the increase of nutrient
385 leaching) on the environment.;
386 Future studies should take into consideration the effects of other organic amendments not only in
387 relation to soil and plant nutrient availability, but also on the effects that compost decomposition
388 could have on the amount of CO₂ emitted or sequestered by the orchard, and the impact of
389 macronutrient dynamics on soil microbial communities structure and activity.

390

391

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395

396 **Authors Contribution**

397 **Conceptualization:** Elena Baldi, Moreno Toselli; **Methodology:** Elena Baldi; **Formal analysis and**
398 **investigation:** Elena Baldi, Martina Mazzon, Maurizio Quartieri, Luciano Cavani; **Writing – original**
399 **draft preparation:** Martina Mazzon; **Writing – review and editing:** Martina Mazzon, Elena Baldi,

400 Luciano Cavani; **Resources:** Moreno Toselli, Claudio Marzadori; **Supervision:** Moreno Toselli,
401 Claudio Marzadori.

402

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