Differential Uptake, Distribution within Tissues, and Use Efficiency of Manganese, Iron, and Zinc by Olive Cultivars Kothreiki and Koroneiki

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Abstract. Three-month-old rooted olive cuttings (*Olea europaea* L., cvs. Koroneiki and Kothreiki of ≈20 to 25 cm in height) were grown outdoors for 140 days (from 30 May until 17 Oct.) under ambient conditions in black plastic bags containing 3 kg of soil. Three soils from different parent material (Marl, Gneiss schist., and Peridotite) and with different physicochemical properties were chosen. In all the soils, ‘Kothreiki’ produced significantly greater total plant biomass compared with ‘Koroneiki’. Furthermore, between the two cultivars studied, ‘Kothreiki’ absorbed significantly greater quantity of manganese (Mn), iron (Fe), and zinc (Zn) per plant compared with ‘Koroneiki’. In all the soils, significantly greater concentrations of Mn, Fe, and Zn were recorded in the root system of both cultivars compared with those of leaves and stems. Between the two cultivars studied, ‘Kothreiki’ had greater percentage of the total Mn content distributed in the root system (74% to 80%) than ‘Koroneiki’ (44% to 56%). That high ability of ‘Kothreiki’ to accumulate Mn in its root system could possibly be advantageous in soils with high Mn concentrations and could constitute a detoxification mechanism to olive trees, protecting the above-ground part of the tree from Mn toxicity. Furthermore, greater concentrations of magnesium (Mg) were recorded in the root system of the olive plants than in leaves and stems, whereas potassium (K) and calcium (Ca) concentrations were greater in leaves compared with those of other tissues (roots and stems). The total per plant quantity of Ca, Mg, and K was significantly greater in the cultivar Kothreiki than ‘Koroneiki’ in all the soils tested. On the other hand, ‘Kothreiki’ presented significantly lower use efficiency of Mn in Marl and Gneiss schist soils, and that of Fe and Mg in all soils, so ‘Koroneiki’ could be considered as a Mn- and Fe-efficient olive cultivar, whereas ‘Kothreiki’ was Mn- and Fe-inefficient.

Differential uptake of a nutrient element by various plant species or cultivars has been referred to by many authors (Damon and Rengel, 2007; Jiang, 2008; Rengel and Damon, 2008; Shuxin et al., 2000). Furthermore, differential distribution, especially of micronutrients, between cultivars of the same plant species is of great importance in cases of micronutrient deficiencies and toxicities. In cases of micronutrient toxicity, it is important to choose genotypes with low uptake and transport from root to shoot of the specific element, like for example happens with manganese (Mn) in Mn toxicity conditions. In that case, low transport of Mn from

root to shoot, in many plant species, is the result of the oxidation of Mn²⁺ to Mn⁴⁺ (El Jaoual and Cox, 1998). In contrast to that, in cases of micronutrient deficiency, the chosen genotypes should have great uptake capacity and transport of the particular element from the root system to the leaves (Rengel, 2001). In addition to that, high internal nutrient use efficiency is also another property that one genotype should have under those conditions (Jiang, 2006; Jiang and Ireland, 2005).

For the olive tree, although it is considered a species with great capacity to survive and produce under low-fertility soils, almost nothing has been investigated so far about micronutrient absorption, distribution, and use efficiency as well as whether genotypic differences exist among olive cultivars concerning micronutrient absorption [especially Mn, iron (Fe), and zinc (Zn)] and nutrient use efficiency, which, for example, exist in some crop cultivars (Jiang, 2006, 2008; Rengel, 2001). For that purpose, two well-known, widely cultivated Greek olive cultivars

(Koroneiki as an oil-producing cultivar and ‘Kothreiki’ as a dual-purpose one) were used in this study. ‘Koroneiki’ is resistant to drought and winds, whereas ‘Kothreiki’ is very resistant to cold and it can be cultivated up to 800 m altitude (Therios, 2005).

The aim of the present investigation was to find possible genotypic differences between the two previously mentioned olive cultivars in the absorption, distribution among various tissues, and use efficiency of Mn, Fe, and Zn in each of the three soils used. To have a better and global view of the mineral nutrition of these two olive cultivars in the three soils used, we also studied the absorption, distribution, and use efficiency of the macronutrients calcium (Ca), magnesium (Mg), and potassium (K). Three soils from different parent material (Marl, Gneiss schist., and Peridotite) and with different physicochemical properties were chosen as a medium for plant growth.

Materials and Methods

Plant material and soil sampling. Three-month-old rooted olive cuttings (*Olea europaea* L., cvs. Koroneiki and Kothreiki ≈20 to 25 cm in height) were grown outdoors for 140 d (from 30 May to 17 Oct.) under ambient conditions in black plastic bags containing 3 kg of soil. The plants of each cultivar were randomized and separated, based on their height and initial total fresh weight, in three similar groups (corresponding to the three soils used) and six replicates per cultivar and per soil type were included. The total number of plants was 36 (three soils × two cultivars × six replicates). Three soils, derived from different parent material (Marl, Gneiss schist., and Peridotite) and having different properties, were included in the study. The soils were collected around the city of Thessaloniki, i.e., Epanomi (Marl), Souroti (Gneiss schist.), and Galatista (Peridotite), and represent the three basic soil types on which olive tree is growing in the region of Thessaloniki, Macedonia, northern Greece. All these soils belong to the Entisols (Orthents) according to the Soil Taxonomy (1975) system. The soil samples were collected from the upper 60 cm of each soil, where most of the olive root system is usually growing. This soil layer of 60 cm included A_p and A_c horizons in the Marl soil, A_p in the Gneiss schist., and A and B horizons in the Peridotite soil. During the period of experimentation, the plants were irrigated three times a week until the end of August and two times a week from the beginning of September to 17 Oct. with 200 mL of distilled water.

Soil sample analysis. After collection, soil samples were dried at room temperature, separated from stones, and sieved to pass a 10-mesh screen before analyses. General chemical analyses as well as extraction of micronutrients were conducted in each one of the three soils. General chemical analyses of the soils included the pH measurement; the percent content of organic matter; the

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Table 1. Physicochemical properties of the three soils (from parent material Marl, Gneiss schist., and Peridotite) (in each soil type six samples were included).

Soil/parent material	Sand	Clay	Loam	Texture	Organic matter (%)	pH	CaCO ₃ (%)	Calcium	Magnesium	Potassium
	(%)							(mEq/100 g soil)		
Marl	62.4	14.8	22.8	SCL	2.88	7.63	3.5	36.90	2.25	1.4
Gneiss schist.	68.4	20.8	10.8	SL	1.68	7.15	1.3	10.68	2.17	1.2
Peridotite	52.4	26.8	20.8	SCL	4.44	7.97	15.4	36.21	2.46	6.7

SCL = sandy clay loam; SL = sandy loam.

exchangeable cations Ca, Mg, and K; the particle size analysis; and the percent CaCO₃. The pH was determined in soil with distilled water (solution 1:1) (Bates, 1964), the organic matter with the K₂Cr₂O₇ method (Allison, 1965), the interchangeable cations according to the method of CH₃COONH₄ pH 9 (pH 9 was chosen to reduce the solubilization of CaCO₃ as the pH values of the three soils were above 7) (Alifragis and Papamichos, 1995; Bower et al., 1952), and the particle size analysis according to the 'Bouyoucos' method. According to Klute (1986), 'Bouyoucos' method provides generally good results for particle soil analysis. Finally, the percent CaCO₃ content was determined with the calcium meter method, whereas the extraction of Mn, Fe, and Zn in the three soils was conducted with the DTPA method (Alifragis and Papamichos, 1995).

Plant growth parameters. Once the plants were harvested (at the 140th day), shoot length as well as fresh and dry weight of leaves, stems, roots, and total plant fresh and dry weights were measured. Samples were initially weighed (fresh weight), then washed with tap and afterward with distilled water, dried at 75 °C for 24 h, and weighed again (dry weight).

Manganese, iron, zinc, calcium, magnesium, and potassium concentrations in plant tissues. After the plants were separated into stems, roots, and leaves, they were washed once with tap and twice with distilled water, dried at 75 °C for 24 h, and the organs were milled to a fine powder to pass a 30-mesh screen. A portion of 0.5 g of the fine powder of each sample was dry-ashed in a muffle furnace at 515 °C for 5 h. Then, the ash was dissolved in 3 mL of 6 N hydrochloric acid and diluted with double distilled water up to 50 mL and the concentrations of the elements Ca, Mg, K, Mn, Fe, and Zn were determined by atomic absorption spectroscopy (Perkin-Elmer 2340, Waltham, MA). The concentrations of the microelements were expressed in micrograms per gram dry weight (DW), whereas those of macronutrients in percent DW. Multiplying the concentration of each nutrient (micrograms or milligrams per gram DW) found in each plant part by its dry weight, the content (absolute quantity) of each nutrient per plant part at the end (at the 140th day) was calculated. By addition of the nutrient contents of different plant parts, total nutrient content (micrograms or milligrams) per plant and thus total nutrient uptake per plant was computed. Calculating for each olive cultivar, and for all soils, the absolute quantities of all nutrients in the different tissues (leaves, stem, and root) and by dividing with the corresponding, for each nutrient, total per

plant quantity, the percent distribution of the nutrients in the three tissues (leaves, stem, and roots) is calculated. Finally, the nutrient use efficiency of each nutrient, which is defined as the amount of biomass produced per unit of nutrient, was further calculated (Chapin and Van Cleve, 1991).

Statistics. All data were statistically analyzed by using the SPSS software package (SPSS 8.0.1 for Windows, Chicago, IL) and, particularly, for comparison of means between the two olive cultivars in each one of the three soils, *t* test was performed for *P* ≤ 0.05.

Results

Soil properties. The physicochemical properties of the three soils are presented in Table 1. The soils from parent material Marl and Peridotite were sandy clay loam, whereas that from Gneiss schist. was sandy loam (SL). The pH of the soil from parent material Gneiss schist. was 7.15, whereas that of the other two soils (from parent material Marl and Peridotite) was 7.63 and 7.97, respectively. The organic matter content (%) of the Gneiss schist. soil was relatively low, whereas that of the other two soils was sufficient and ranges between 2.88% and 4.44%. The CaCO₃ (%) content was medium (15.4%) in the Peridotite soil, whereas in the other two soils, it was very low. Among the exchangeable cations, Ca dominates in the Marl and Peridotite soils (which are saturated in Ca), whereas in Gneiss schist., it was ≈27% of that in the other two soils. Potassium was more than five times greater in the Peridotite soil compared with the other two soils. The concentrations of Mg were approximately equal in the three soils (Table 1). The cation exchange capacity (CEC) values for the Marl, Gneiss schist., and Peridotite soils were 43%, 17%, and 48%, respectively, whereas the water-holding capacity values of the three studied soils were 29%, 22%, and 30% for the Marl, Gneiss schist., and Peridotite soils, respectively. From Table 2 it is evident that the greatest concentration of the DTPA-extractable Mn was recorded in the Peridotite soil, whereas in the other two soils, it was only ≈50% of that in the Peridotite soil. The concentration of Fe is 3, 4, and 5 mg·kg⁻¹ soil in Marl, Peridotite, and Gneiss schist. soil, respectively, whereas the concentrations of Zn were approximately equal in the three soils.

Plant growth parameters. Between the two cultivars and in all soils, 'Kothreiki' had significantly greater total plant biomass compared with 'Koroneiki'. Particularly, 'Kothreiki' had significantly greater fresh

Table 2. Manganese (Mn), iron (Fe), and zinc (Zn) concentration (mg·kg⁻¹ of soil) in the three soils after DTPA extraction.

Soil/nutrient element	Mn	Fe	Zn
Marl	7	3	1.5
Gneiss schist.	6	5	1.5
Peridotite	12	4	1.0

and dry weights of root and leaves compared with 'Koroneiki'. The fresh weight of the root system of 'Koroneiki' was ≈41%, 61%, and 32% of that of cultivar Kothreiki in the Marl, Gneiss schist., and Peridotite soils, respectively (Table 3).

Concentrations of nutrient elements in plant tissues, total plant content of manganese, iron, zinc, calcium, magnesium, and potassium and nutrient use efficiency. 'Kothreiki' (in all soils) absorbed significantly greater quantities of Mn, Fe, and Zn compared with that absorbed by 'Koroneiki' (Fig. 1). In both olive cultivars and all soils used, greater concentrations of Mn, Fe, Zn, and Mg were recorded in the root system than in leaves and stems, whereas greater concentrations of K and Ca were found in leaves than in the other tissues (root, stems) (Table 4). The total plant content of Ca, Mg, and K was also significantly greater in the cultivar Kothreiki than in 'Koroneiki' in all soils (Fig. 1).

From Table 5 it is concluded that in all soils, both olive cultivars had the greatest percentage of the total per plant Mn distributed in the root. 'Kothreiki' had in all soils a greater percentage (74% to 81%) of the total per plant Mn distributed in the roots than 'Koroneiki' (44% to 56%). Concerning Fe distribution in root, stem, and leaves, more than 90% of the total per plant Fe was distributed in the root system and only ≈0.6% to 2.4% in leaves. Zinc, in all soils, was mainly distributed in the root system than in leaves and stem. 'Kothreiki' had greater distribution (%) of the total per plant Zn in the root system (and lower in the stems) than 'Koroneiki'. It is remarkable that although a much greater proportion of the total per plant content of Mn and Zn was recorded in the root system of 'Kothreiki' compared with that of 'Koroneiki', no significant differences were found in the percentage of the total per plant content of Mn and Zn distributed in the leaves of both cultivars. Calcium and K were generally equally distributed among the three vegetative tissues (root, stem, and leaves), in both olive cultivars and all soils, whereas Mg was mainly distributed in the root system (data not shown).

Table 6 shows the use efficiency of all nutrients for both olive cultivars and in all

Table 3. Plant growth parameters of the olive cultivars Koroneiki and Kothreiki grown in three soils with different physicochemical properties.

Soil	Cultivar	Shoot length (cm)	Root wt (g)		Stems wt (g)		Leaves wt (g)		Root/stem+ leaves	Total plant wt (g)	
			FW	DW	FW	DW	FW	DW		FW	DW
Marl	Kor	105 a ²	34.04 b	10.79 b	25.60 a	13.68 a	15.53 b	7.32 b	0.82 b	75.17 b	31.80 b
	Koth	117 a	82.65 a	16.02 a	25.22 a	13.34 a	22.39 a	10.80 a	1.72 a	130.26 a	40.17 a
Gneiss schist.	Kor	94 a	61.60 b	10.70 b	17.21 a	9.67 a	11.05 b	5.15 b	1.73 b	89.86 b	25.52 b
	Koth	90 a	101.49 a	16.47 a	18.12 a	9.96 a	14.75 a	7.50 a	3.07 a	134.36 a	33.93 a
Peridotite	Kor	114 a	33.27 b	9.58 b	23.03 a	12.70 a	16.14 b	7.37 b	0.86 b	72.44 b	29.65 b
	Koth	123 a	103.31 a	20.19 a	25.95 a	13.90 a	21.62 a	10.36 a	2.17 a	150.88 a	44.46 a

²The different letters in the same column symbolize statistically significant differences between the two cultivars in each of the three soils for $P \leq 0.05$ (n = 6) (SPSS, Chicago, IL; *t* test).

FW = fresh weight; DW = dry weight.

Fig. 1. Total per plant quantity of manganese (A), iron (B), zinc (C), calcium (D), magnesium (E), and potassium (F) absorbed by the olive cultivars Koroneiki and Kothreiki when each one of them was grown in three soils (from parent material Marl, Gneiss schist., and Peridotite) with different physicochemical properties.

soils. As is obvious from this table, 'Kothreiki' had significantly lower use efficiency of Mn in Marl and Gneiss schist. soils and that of Fe in all soils compared with the

cultivar Koroneiki. In contrast to that, Zn use efficiency did not differ between the two cultivars studied in each of the three soils. From the same table, it is concluded that

irrespective of the soil where the olive plants were grown, Ca use efficiency and K use efficiency did not differ between the studied cultivars. Magnesium was more efficiently

Table 4. Concentrations of manganese (Mn), iron (Fe), zinc (Zn), calcium (Ca), magnesium (Mg), and potassium (K) in the leaves, stems, and roots of the olive cultivars Koroneiki and Kothreiki when each one of them was grown in three soils (from parent material Marl, Gneiss schist., and Peridotite) with different physicochemical properties.

Soil	Cultivar	Organs	Mn	Fe	Zn	Ca	Mg	K
			(μg·g ⁻¹ DW)			(% DW)		
Marl	Kor	Leaves	16 b ^z	58 a	12 a	0.84 b	0.08 a	0.81 a
	Koth		26 a	62 a	11 a	1.08 a	0.07 a	0.80 a
Gneiss schist.	Kor		12 b	57 a	14 a	1.03 a	0.10 a	1.00 a
	Koth		19 a	51 a	11 a	0.97 a	0.06 b	0.79 a
Peridotite	Kor		21 a	70 a	19 a	0.88 b	0.14 a	0.98 a
	Koth		26 a	58 a	10 b	1.06 a	0.09 b	0.96 a
Marl	Kor	Stems	28 a	53 a	9 a	0.50 a	0.03 a	0.43 b
	Koth		21 a	42 a	7 a	0.58 a	0.04 a	0.55 a
Gneiss schist.	Kor		23 a	54 a	14 a	0.55 b	0.04 a	0.34 b
	Koth		21 a	52 a	10 b	0.68 a	0.04 a	0.50 a
Peridotite	Kor		44 a	139 a	13 a	0.56 a	0.06 a	0.38 a
	Koth		23 b	48 b	8 b	0.62 a	0.05 a	0.47 a
Marl	Kor	Root	46 b	1590 b	19 a	0.99 a	0.15 b	0.69 a
	Koth		100 a	3763 a	24 a	0.68 b	0.27 a	0.75 a
Gneiss schist.	Kor		34 b	1213 b	28 a	0.63 a	0.19 b	0.54 b
	Koth		94 a	4600 a	31 a	0.60 a	0.33 a	0.59 b
Peridotite	Kor		58 b	2350 b	19 a	0.64 a	0.18 b	0.43 b
	Koth		93 a	3720 a	20 a	0.68 a	0.35 a	0.58 a

^zThe different letters in the same column symbolize statistically significant differences between the two olive cultivars in each of the three soils for $P \leq 0.05$ (n = 6) (SPSS, Chicago, IL; *t* test).

DW = dry weight.

Table 5. Distribution (%) of the total per plant quantity of manganese (Mn), iron (Fe), and zinc (Zn) in the three vegetative tissues (root, stem, and leaves) of the olive cultivars Koroneiki and Kothreiki when each one was grown in three soils (from parent material Marl, Gneiss schist., and Peridotite) with different physicochemical properties.

Soil	Cultivar	Micronutrient	Root	Stem	Leaves
Marl	Kor	Mn	50.2 b ^z	38.0 a	11.8 a
	Koth		74.1 a	12.8 b	13.1 a
Gneiss schist.	Kor		56.5 b	34.2 a	9.3 a
	Koth		81.3 a	10.8 b	7.9 a
Peridotite	Kor		44.0 b	44.0 a	12.0 a
	Koth		76.0 a	12.9 b	11.1 a
Marl	Kor	Fe	93.7 a	3.9 a	2.4 a
	Koth		98.0 a	0.9 b	1.1 b
Gneiss schist.	Kor		94.0 a	3.7 a	2.3 a
	Koth		98.8 a	0.6 b	0.6 b
Peridotite	Kor		90.8 a	7.1 a	2.1 a
	Koth		98.3 a	0.8 b	0.9 b
Marl	Kor	Zn	49.3 b	29.6 a	21.1 a
	Koth		64.4 a	15.6 b	20.0 a
Gneiss schist.	Kor		59.1 b	26.7 a	14.2 a
	Koth		73.7 a	14.3 b	12.0 a
Peridotite	Kor		37.3 b	33.9 a	28.8 a
	Koth		65.3 a	18.0 b	16.7 b

^zThe different letters in the same column symbolize statistically significant differences between the two olive cultivars in each of the three soils for $P \leq 0.05$ (n = 6) (SPSS, Chicago, IL; *t* test).

used by ‘Koroneiki’ than by ‘Kothreiki’ in all soils.

Discussion

According to Alifragis and Papamichos (1995), the concentrations of Mn, Fe, and Zn determined in the three soils, with the DTPA method, were moderate to sufficient. The pH of the soil from parent material Gneiss schist. was almost neutral, whereas that of the other two soils (from parent material Marl and Peridotite) was slightly alkaline (Table 1). Generally, when the pH is alkaline, the non-available (oxides) forms of Mn and Fe are present in the soils. However, pH values did not reduce significantly Mn and Fe levels in the leaves, because their levels were greater than 12 and 50 μg·g⁻¹ DW for Mn and Fe, respectively (Table 4). Concentrations

greater than 20 μg·g⁻¹ DW for Mn and in the range between 50 and 150 μg·g⁻¹ DW for Fe are referred by Panagiotopoulos (2001) as sufficient ones, whereas in the range between 5 and 20 μg·g⁻¹ DW for Mn was relatively deficient. It should be pointed out that under alkaline pH conditions, Mn and Fe complexes with organic matter constitute 80% to 95% of the total soluble Mn and Fe. The stability of these complexes increases with the increase of soil pH. Therefore, alkaline pH does not necessarily imply Mn and Fe deficiency of plants (Keramidas, 1997). This is what probably happened in the Peridotite soil. Indeed, the concentrations of Mn (greater than 20 μg·g⁻¹ DW) and Fe (greater 50 μg·g⁻¹ DW) were sufficient in the leaves of both olive cultivars when grown in the Peridotite soil. The CaCO₃ content (%) of the Peridotite soil was much higher compared

with those of the Gneiss schist. and Marl (Table 1). However, the effect of the high CaCO₃ content in the case of the Peridotite soil was not inhibitory for Fe and Mn absorption by olive plants. Generally, the most appropriate soils for growth and fruiting of olive trees are the SL after sufficient fertilization with N, K, and P and with adequate water content (Therios, 2005). In our case, although the Gneiss schist. soil was a SL one, plant growth was less than in the other two soils (from parent material Marl and Peridotite). This happened probably as a result of the lower (%) organic matter content and CEC (only 17% compared with those of 43% and 48% of Marl and Peridotite soils, respectively) and water-holding capacity (22%, compared with those of 29% and 30% of Marl and Peridotite soils) than those of the other two soils.

In all the soils, both cultivars had the greatest part of total Mn distributed in their root system. ‘Kothreiki’ had a greater percentage of the total root Mn content distributed in the root system (74% to 80%) than ‘Koroneiki’ (44% to 56%) (Table 5). That high ability of ‘Kothreiki’ to accumulate Mn in its root system could be possibly advantageous in soils with high Mn concentrations and could constitute a detoxification mechanism to olive trees, protecting the above-ground part of the tree from Mn toxicity. Under Mn excess/toxicity conditions also, other plant species such as *Mentha spicata*, *Citrus* sp., *Pseudoacacia* sp., *Juglans regia*, *Populus* sp. and *Eucalyptus* sp. accumulate most of the total Mn absorbed in the root system to protect their shoots from Mn toxicity (Asrar et al., 2005; Chatzistathis and Alifragis, 2004; Loneragan, 1988; Papadakis, 2004). It should be pointed out that the same tendency of high Mn accumulation in the root system of ‘Kothreiki’ was also observed in our previous hydroponic experiments testing a great range of Mn concentrations

Table 6. Nutrient use efficiency (mg of the total plant DW/ μ g of the total per plant quantity of micronutrient or mg of the total per plant quantity of macronutrient) of the olive cultivars Koroneiki and Kothreiki when each of them was grown in three soils (from parent material Marl, Gneiss schist., and Peridotite) with different physicochemical properties.

Soil	Cultivar	Mn UE	Fe UE	Zn UE	Ca UE	Mg UE	K UE
		(mg of the total plant DW/ μ g of the total per plant quantity of micronutrient)			(mg of the total plant DW/mg of the total per plant quantity of macronutrient)		
Marl	Kor	31.85 a [*]	1.73 a	77.53 a	134.18 a	1180.31 a	164.95 a
	Koth	18.68 b	0.65 b	68.08 a	132.75 a	716.61 b	143.69 a
Gneiss schist.	Kor	39.87 a	1.84 a	51.04 a	146.97 a	878.05 a	179.51 a
	Koth	17.94 b	0.44 b	49.15 a	141.64 a	534.31 b	164.34 a
Peridotite	Kor	23.33 a	1.19 a	61.75 a	150.23 a	849.40 a	183.32 a
	Koth	18.00 a	0.58 b	72.88 a	133.20 a	515.50 b	157.47 a

^{*}The different letters in the same column symbolize statistically significant differences between the two cultivars in each of the three soils for $P \leq 0.05$ ($n = 6$) (SPSS, Chicago, IL; t test).

DW = dry weight; Mn = manganese; UE = use efficiency; Fe = iron; Zn = zinc; Ca = calcium; Mg = magnesium; K = potassium.

(from 0 to 640 μ M) in the nutrient solution (Chatzistathis, unpublished data). Differences between genotypes of the same species in growth, absorption, and distribution of Mn within tissues have been also reported by researchers in other species such as soybean, *Triticale*s, and *Pseudotsuga menziesii* (Ducic et al., 2006; Heenan and Carter, 1976; Quartin et al., 2001) and are in accordance with our results.

Considering the distribution of Fe between root system and shoot, the greater part of it accumulated in the root system (greater than 95% of the total per plant content). A similar trend was recorded for Zn (but the percentage distributed in the root system was much less than 95%) (Table 5). Although 'Kothreiki' absorbed significantly greater quantities of Fe and Zn compared with 'Koroneiki', the concentrations of Fe and Zn in its leaves were, in almost all cases, not greater than those of 'Koroneiki' (Table 4). This probably happened because a much greater percentage of the total per plant Fe and Zn content was retained in the root system of 'Kothreiki' (Table 5). Therefore, the root system exerts a buffering role controlling Fe and Zn levels in the top of the tree. Calcium and potassium were equally distributed in roots, stems, and leaves in both olive cultivars and in all soils, whereas Mg was mainly distributed in the root system (data not shown). Furthermore, the concentrations of all nutrient elements in the leaves of both olive cultivars were in the normal range, with the exception of Mn concentration in the leaves of 'Koroneiki', when cultivated in the Gneiss schist. and Marl soils (12 and 16 μ g·g⁻¹ DW, less than 20 μ g·g⁻¹ DW) (Table 4), which could be characterized as relatively, but not seriously, deficient according to Panagiotopoulos (2001).

The examined cultivars accumulated different amounts of micronutrients (Fig. 1). However, cultivar Kothreiki, which accumulated more Mn and Fe, had significantly lower use efficiency of Mn in Marl and Gneiss schist. soils and that of Fe in all soils compared with 'Koroneiki', whereas Zn use efficiency did not significantly differ between the two cultivars in each of the three soils (Table 6). Although 'Kothreiki' absorbed and accumulated significantly greater quantities of Mn and Fe in all soils compared with 'Koroneiki', the increase of its total plant

biomass was not so sufficient to benefit from the greater total uptake of these two elements. The "retention" of a great part of the total per plant content of Mn and Fe in the root system and the limited transport to the shoot means that 'Kothreiki' had lower use efficiency of Mn and Fe compared with 'Koroneiki'. Jiang (2006) and Jiang and Ireland (2005) state that Mn efficient wheat cultivars own this ability to a better internal use of Mn rather than to a higher plant Mn accumulation. Based on that remark of the mentioned researchers, it could be concluded that 'Kothreiki' is not probably well adapted in Mn-deficient soils. According to Rengel (2001), who conducted a review on genotypic differences in micronutrient use efficiency of many crops, micronutrient-efficient genotypes were capable of increasing the available soil micronutrient pools through changing chemical and microbiological properties of the rhizosphere as well as by growing thinner and longer roots and by having more efficient uptake and transport mechanisms. In our case, 'Koroneiki' could be considered as a Mn- and Fe-efficient one compared with 'Kothreiki' because of its better transport system of these two elements from the root to the shoot. According to Maruyama et al. (2005), who conducted a comparison of iron availability in leaves of barley and rice, the difference in the Fe acquisition ability between these two species was affected by the differential mugineic acid secretion. Maybe a similar mechanism is working in the two olive cultivars studied. In all soils, Ca use efficiency and K use efficiency did not significantly differ between the studied cultivars (Table 6). In contrast to that, Damon and Rengel (2007) and Rengel and Damon (2008), who studied the K efficiency in different wheat genotypes under glasshouse and field conditions, and different crops, respectively, found that this efficiency differed between crops or genotypes of the same species.

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