Soil properties in rainfed and irrigated olive groves following alternative cultivation practices

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Abstract

Olive tree pruning residue and olive waste represent a great amount of organic materials which are produced during a short period. The application of organic materials to land is a common practice in sustainable agriculture. However, its implementation in olive groves under different irrigation regimes has not been systematically tested. The aim of this work was to study the effect of alternative carbon input techniques (wood shredded, pruning residues, returning of olive mill wastes the field with compost) on soil chemical and microbial properties in relation to irrigation conditions (irrigated and rainfed olive orchards). The results showed that averaged over the irrigation conditions, carbon inputs failed to significantly increase soil organic carbon and nutrients in soils mainly due to the short term application of organic materials. However the improvement of soil quality in olive groves via recycling organic materials from olive mill wastes and pruning depends on irrigation conditions. In fact, favorable soil water conditions in irrigated fields compared to rainfed ones and nutrient enrichment of soil by carbon inputs improve soil fertility. Levels of many soil chemical and microbial properties were significantly higher under the canopy as compared to outside the canopy indicating that appropriate cultivation practices, such as recycling of olive mill wastes and residues, can improve soil fertility. Furthermore, significant decreases with soil depth were registered for many soil properties and particularly for soil organic carbon indicating the potential of surface soil in olive groves to sequester carbon is high, whereas carbon inputs and irrigation conditions did not contribute to subsoil C content.

Key words: carbon inputs, soil, chemical properties, microbial properties, olive groves, irrigation.

Introduction

Olive (*Olea europaea* L.) is a widely cultivated tree crop in the semiarid Mediterranean region. Intensive cultivation practices are associated to low soil fertility and degradation of water resources [1].The most important problem of agriculture in Greece is the low content of organic matter, which is the most restrictive resource for food production and the sustainability of Greek agriculture. Low levels of organic matter is a result of the mechanization of agriculture, the lack of use of organic fertilizers, use of chemical fertilizers, pesticides, monoculture, burning debris, fallow, etc.

Optimizing carbon balance in olive groves may improve soil fertility and biodiversity and contribute to climate change mitigation, since carbon is removed from the atmosphere. During olive growth a large quantity of plant residues are produced while high loads of both liquid and solid olive mill wastes produced during the extraction of olive oil. Materials such as oil mill wastes, leaves and stems of olive have been studied in the past for their suitability for composting, with encouraging results. [2,3] reported that when the long term recycling of plant residues is combined with application of compost in soil in Mediterranean tree crops, then organic matter is substantially increased. Mulch using plant residues is becoming increasingly popular by farmers also because it reduces the need for weed control measures [4] and reduces soil and nutrient losses [5]. The above soil-management systems are an alternative for improving the soil quality and fertility in sustainable agricultural system [6]. However, the implementation for these techniques has not been systematically tested under the prevailing conditions of the Greek/Mediterranean olive forest. In addition, irrigation, although favoring the productivity of trees, can often have an adverse effect on the properties of the soil and hence the productivity [7].The adverse effects result from the water irrigation quality, the application method and soil properties. A LIFE+ project was initiated (oLIVE-CLIMA; LIFE 11/ENV/000942) aiming to introduce alternative management practices in olive tree crops that lead to increase carbon dioxide uptake by plants. They also trigger carbon sequestration from the atmosphere and reverse the trend of soil organic matter decline, erosion and desertification. The aim of this work was to determine the effects of organic inputs and irrigation conditions on some soil chemical and microbial properties in Mediterranean olive orchards. This study also examined the spatial distribution of soil properties in relation to the distance from the olive tree trunk.

Materials and Methods

Study area

The area of study is located in the region of Peza, prefecture of Heraklion, Island of Crete, South Greece. Average precipitation is 500 mm; most of it falls between October and April, while no precipitation is expected during summer. Limestones cover almost 40% of the total area (8300km^2) of the island of Crete; dolomites, marbles and alluvial deposits are also seen. Soils in the area under study are generally silty clayey, clayey, no well developed (without diagnostic horizons), highly eroded, and partly protected by old and no preserved terraces. Soils are classified as Entisol *xerorthent*, [8].

Experimental design

Forty soil parcels of olive groves in the region of Peza, Crete, were selected. The size of soil parcels varies between 0.2-0.8 hectares. Carbon input practices (CT) were applied on the half of the irrigated and rainfed soil parcels (Irrigation conditions IC; 20 rainfed and 20 irrigated), while the remaining ones were used as controls. Carbon inputs were a combination of chopped pruning residues, with compost derived from recycling byproducts of a 3-phase olive mill. Weeds were also maintained and cut before spring.

The compost produced from mixing olive pomace, leaves, and chopped pruning residue at a ratio of 1:1:2 where 2 kg $CO(NH_2)_2$ per m^3 of mixture was added. The compost was supplied once at a rate of 2.9 t ha^{-1} in September 2014 and it had 14 C/N ratio, pH = 7.5 and contained on dry matter basis, 42.8 % total C, 3.14 % total N, 0.12% total P and 0.86 % total K. The compost dose to be applied depended on the available amount of the materials derived as byproducts from cultivation of olive groves. Soil was supplemented with chopped pruning residues from the same groves (f.w. 2.4 t ha^{-1} in August 2013 and 2.3 t ha^{-1} in September 2014). Pruning residues contained on dry matter basis, 57 % total C, 0.95 % total N, 0.72 % total K and 0.095% total P. In addition weeds were cut at the beginning of March 2013 and 2014 and left on soil. They contained 51.26 % C, 1.82 % N, 0.32 % P and 2.45% K.

A soil sampling campaign took place during the period January-February 2015. In each soil parcel six composite soil samples were taken from 0-10 cm of depth, at equal intervals, along a straight line joining the trunk of the tree with the middle of the distance from the nearest tree of the next tree series (sample codes: 1, 2, 3, M-1, M, M+1). The first three samples were under the tree canopy (sample codes: 1, 2, 3). An additional composite sample was taken at the depth of 10-40 cm (sample code: 10-40cm). Samples taken from 0-10 cm were collected since surface soil is the main part of what carbon inputs contribute to soil organic matter and is more sensitive to changes in organic matter content. In addition about half the microbial biomass is located in the surface 10 cm of a soil profile and most of the nutrient release also occurs here. A general assessment of soil organic matter content below 10 cm took place by taking soil sample at the depth 10-40 cm in the close vicinity of active olive roots. Main properties of soil in control fields are shown in Table 1.

Soil chemical analysis

Soil analysis was carried out via standard methodologies [9]. Particle- size distribution was determined by the Bouyoucos method; pH and EC were measured in paste extract with a pH/EC meter equipped with a glass electrode (Mettler Toledo, Switzerland); carbonates by using a Bernard calcimeter; total N by the Kjeldahl method [10]; soil organic C (SOC) was determined by sulfochromic oxidation [11]; available P was determined by sodium hydrogen carbonate extraction [12] exchangeable K, using $BaCl_2$ extraction [13], Determination of NH_4^+-N, NO_3^-, was performed in 1:10 water extracts using Dionex-100 Ionic Chromatography (DX 1-03, USA). Humic acids (HA) and fulvic acids (FA) in soil samples were determined according to [14].

Soil microbiological analysis

The microbial activity in soil samples was indirectly measured by the determination of the soil basal microbial respiration (SBMR), which is the amount of CO_2 evolution, from moist (50-60% of the water holding capacity WHC); soil samples incubated at 22 + 2 ^oC, for 24 h. The CO_2 evolved was determined by titrating 10 mL of the NaOH solution with 0.1 N HCl (Ohlinger, 1995). The SBMR was expressed as mg CO_2–C kg ^{1} soil h^{-1} on a soil dry weight basis (105^o C, 24 h). Microbial biomass C (MB-C) was determined by substrate-induced respiration (SMBR), after the addition of 1% glucose [15] and expressed as mg C kg $^{-1}$ dry soil. The SMBR/MB-C ratio was also determined and reported as metabolic quotient (qCO_2, mg CO_2–C kg^{-1} MB-C h^{-1}) [16].

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using carbon treatments (CT), irrigation conditions (IC) and distance from tree (TD) as factors. Before the analysis data were tested for homogeneity, and then subjected to Duncan's multiple range test (a = 0.05).

Results and discussion

Effect of carbon treatments (CT)

The results showed that carbon treatments (CT) increased significantly NH_4^+, whereas exchangeable K, and available P significantly decreased compared to control soil (Table 2). Soil organic carbon and N, NO_3^-, were not significantly influenced by CT which may have ascribed to their low nutrient content, as well as to the short term application of organic materials on soil. [2,3] reported that when the long term recycling of plant residues is combined with the application of compost, then organic matter content is substantially increased. However, there are studies showed that soil C does not increase as expected in response to application of crop residues [17; 18]. [19] noticed that the difficulty in increasing soil C by crop residue input may be related to decreased microbial carbon use efficiency. This is due to the fact that although microbial respiration should increase linearly with the addition of increased amounts of fresh organic matter, however, the response of the microbial biomass may not be linear due to insufficient inorganic nutrients to form new biomass.

Moreover, FA and HA/FA were significantly decreased by CT compared to control. The lower humification rates indicate lower formation of humic and fulvic acid content in soil than fresh organic matter input in soil which may be ascribed to restrictions to soil biological activity [20].Relatively higher levels of qCO_2 in soils amended with olive residues were obtained indicated stress conditions on soil microflora. Metabolic quotient (qCO_2) is a measure of respiration rate per unit of microbial C and microorganisms that ordinarily respond to a hostile environment by developing defense mechanisms like increasing their respiration per unit of biomass [15]. [21] reported higher rates of organic matter were added to the soils, lower carbon sequestration was observed and *vice versa*. The authors attributed this pattern to the fact that soil microbial activity is stimulated by available organic matter, and may be result of the priming effect [22]. In addition, carbon inputs did not affect significantly SBMR and MB-C (Table 3) compared to the control may be due to the fact that SOC did not changed by CT and therefore soil microbial biomass and microbial activity was not favored by carbon inputs.

Effect of irrigation conditions (IC)

Irrigation conditions (IC) significantly affected the chemical and microbial properties of soils [7, 23, 24]. Soil organic carbon, TN, NH_4^+, available P, exchangeable K, organic fractions (HA and FA), SBMR and qCO2 were significantly higher in irrigated plots compared to rain fed olive groves. This can be ascribed to favourable moisture conditions in irrigated fields which favour residue production and availability of nutrients. Availability of P is favored by soil moisture is attributed to movement of P in mass flow with irrigation waters after saturation of reaction sites near the zone of P application [25]. The irrigation water in the region has an alkaline pH, due to the high concentration in carbonates, particularly Ca^{2+}, Mg^{2+} and K^+, and these properties increase the content of these nutrients in soil.In addition, the significant higher values of MB-C in irrigated parcels as compared to rainfed ones can be due to the increased availability of nutrients and the increased soil moisture conditions, which therefore favor the development of microorganisms and their activity. [26] reported that microbial biomass and population size were among the soil properties that were mainly affected by moisture and the ratio of C:N. On the other hand, mean values of HA/FA were significantly lower in irrigated soils compared to rainfed ones indicating lower humification rates of organic matter, which may be driven by edaphic processes, soil management and/or recent input of organic matter [20] due to more favourable moisture conditions. This may leads to restrictions to soil biological activity. In fact the significant higher levels of qCO_2 on irrigated crops indicated stress conditions on soil microflora.

Effect of CT x IC interactions

Significant CT x IC interactions for TN, NO_3 and FA were recorded (Tables 2 and 3). Total nitrogen and NO_3 increased under CT in irrigated fields compared to the control whereas the above soil parameters were substantially decreased by CT in rainfed parcels. This is may be attributed to better soil water conditions in irrigated fields compared to rainfed ones which promote mineralization of organic matter [27]. In addition, although FA were not affected by CT in irrigated fields, FA were significantly reduced in rainfed soil parcels thus indicating the predominance of HA over FA and high polymerization of humic substances as a result of higher humification

Effect of distance from the tree trunk (TD)

Levels of many soil chemical and microbial properties (SOC, TN, NO_3, Pavail, Kexch, FA, SBMR and qCO_2) were higher under the canopy as compared to outside the canopy (Table 2). The decrease with the distance from the tree trend was significant for available P, exchangeable K, FA and MB-C. Cultivations practices, especially tillage, are restricted under tree canopy while chemical fertilization usually takes place. The area under the tree is richer in organic residues due to the continual dropping of olive leaves, and the greater presence of roots and weeds compared to the area out of the tree canopy [28]. In addition, nutrients in soils out of the tree canopy are subjected to leaching due to rainfall while the replenishment of nutrient loss is limited. In addition root growth is concentrated mainly in the wetted zone in the case of drip irrigation [29] and in this case total N, organic carbon and available nutrients are positively influenced [30]. The greater levels of MB-C determined in samples taken near the points of the rhizosphere of the tree, under canopy, indicated the considerable influence of the root system and high availability of nutrients for the formation of soil microflora. Changes in soil microbial activity are closely related to changes in soil organic matter [31].

[32] reported that no-tillage with residue application was proved to increase the soil microbial community.

The above results indicate improved soil fertility especially in areas closer to the tree trunks. This is of particular importance for soil conservation, erosion control and maintenance soil fertility. Practices such as appropriate planting interval, and recycling of olive mill wastes and residues will contribute to increase the stable carbon, the water holding capacity, and the moisture availability in soil and will therefore improve soil productivity.

Effect of soil depth

With regard to changes of soil properties with depth significant decreases were registered for SOC, inorganic nitrogen (NH_4^+ and NO_3^-), exchangeable K, available P, FA, and MB-C. Maximum values of organic matter and nitrogen were also reported in surface soil layers (up to 10 cm) of olive groves [33, 34]. However, this is not the case for many arable crops and vineyards where SOC can be transported to a deeper soil horizon, contributing to the subsoil C storage [35, 36]. As for the rest of the soil properties, there were no significant depth-related variations. In addition, carbon inputs and irrigation conditions did not contribute to subsoil C content. In fact, there were no significant soil depth x CT and soil depth x IC (data not shown) indicating that neither application of organic matter nor irrigation conditions could significantly influence the depth distribution of soil properties.

Conclusions

The results showed that averaged over the irrigation conditions, carbon inputs failed to significantly increase soil organic carbon and nutrients in soils mainly due to the short term application of organic materials. On the other hand irrigation conditions considerably influenced carboin input effect on soil properties. Favorable soil water conditions in irrigated fields compared to rainfed ones and nutrient enrichment of soil by CT promoted soil fertility. It is very important that soil management practices consider the spatial distribution of soil properties in relation to the distance of the tree trunk. Significant decreases with soil depth were registered for many soil parameters particularly for SOC indicating the potential of surface soil in olive groves to sequester carbon is high, whereas carbon inputs and irrigation conditions did not contribute to subsoil C content. Long term monitoring of soil properties in olive groves under different soil management systems will allow achieving a deeper understanding of carbon input practices on soil quality and will contribute to the development and adaptation by growers' technical recommendations on sustainable soil management in Mediterranean olive groves.

Acknowledgements

With the contribution of the LIFE + financial instrument of the European Union to project LIFE11 ENV/GR/942 OLIVE-CLIMA.

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Table 1a. Main properties of the soil in control plots

Descriptive Statistics (mean values ± standard error)									
Soil depth	Clay %	Silt %	Sand %	pH [(a)]	EC [(a)] mS cm^{-1}	SOC [(a)] g kg^{-1}	TN [(a)] mg g^{-1}	NH_4^+ [(a)] mg kg^{-1}	NO_3^- [(a)] mg kg^{-1}
0-10 cm	37±3.7	27±2.7	36±4.2	7.41±0.014	1.69±0.074	23,164±9,317	3.10±0.15	3,29±0.22	70.47±6.83
10-40 cm	41±2.1	28±1.0	32±1.8	7.49±0.032	1.27±0.093	19,42±2.43	2.55±0.17	3,58±0.69	51.81±6.33

(a) electrical conductivity (EC), soil organic carbon (SOC), total nitrogen (TN), inorganic nitrogen ($NO_3^{-,}$ and NH_4^+), available P-Olsen (Pavail),

Table 1b. Main properties of the soil in control plots

Descriptive Statistics (mean values ± standard error)								
Soil depth	Pavail [(a)] mg kg^{-1}	Kexch [(a)] $cmol_c$ kg^{-1}	Caexch [(a)] $cmol_c$ kg^{-1}	Mgexch [(a)] $cmol_c$ kg^{-1}	HA [(a)] mg g^{-1}	FA [(a)] mg g^{-1}	SBMR [(a)] CO_2–C kg^{-1} soil h^{-1}	MB-C [(a)] mg C kg^{-1} soil
0-10 cm	26±1.7	0.92±0.041	26.7±0.61	1.65±0.07	2.12±0.13	1.19±0.024	0.332±0.035	0.779±0.032
10-40 cm	13.1±1.9	0.62±0.063	26.3±1.98	1.52±0.23	1.67±0.32	0.89±0.067	0.278±0.078	0.624±0.074

(a) Available P (Pavail), exchangeable K (Kexch), exchangeable Ca (Caexch) exchangeable Mg (Mgexch), humic acids (HA), fulvic acids (FA), Soil Basal Microbial Respiration (SBMR), Microbial Biomass Carbon (MB-C)

Table 2. Effects of carbon treatments (CT), irrigation conditions (IC), and distance from the tree trunk (TD) and their interactions on soil pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (TN), inorganic nitrogen (NO_3^-, and NH_4^+), available P (Pavail), exchangeable K (Kexch), humic acids (HA), fulvic acids (FA), Soil Basal Microbial Respiration (SBMR), Microbial Biomass Carbon (MB-C), and metabolic quotient (qCO_2).

F value								
Source [a]	df	pH	EC	SOC	TN	NO_3^-	NH_4^+	Pavail
Carbon treatments (CT)	1	0.545 NS	1.098NS	0.039NS	1.484NS	0.051NS	5.196*	31.819***
Irrigation conditions (IC)	1	0.014NS	2.073NS	16.565***	24.049***	0.956NS	10.269**	8.774**
Distance from tree (TD)	6	1.848NS	3.338**	0.927NS	2.478*	1.273NS	0.383NS	8.638***
CT x IC	6	0.020NS	1.183NS	1.012NS	8.666***	5.184*	0.823NS	1.514 NS
CT x TD	1	1.095NS	2.04 NS	0.235NS	0.418NS	1.560NS	0.350NS	0.751 NS
IC x TD	6	0.963NS	1.101	0.476NS	0.161NS	2.154 NS	0.036NS	1.139 NS
CT x IC x TD	1	0.814NS	0.805	0.493NS	0.119NS	1.903NS	0.284NS	0.492 NS
Mean values ± se [c]								
Main factor		pH	EC [b]	SOC [b]	TN [b]	NO_3^- [b]	NH_4^+ [b]	Pavail [b]
Carbon treatments	Control	7.4±.041	1.92 ± 0.309	22.8±1.06	1.79±0.071	69.7±8.97	3.3±0.24 a	24.0±1.45 b
	Carbon inputs	7.4±.042 *NS*	2.21 ± 0.314 *NS*	22.5±1.11 *NS*	1.66±0.074 *NS*	73.4±7.25 *NS*	4.1±0.24 b	12.3±1.48 a
Irrigation conditions	Irrigated soil	7.4±.043	3.32±0.326	25.8±1.12 b	1.98±.078 b	77.4±7.04	4.3±0.25b	21.2±1.55 b
	Rainfed soil	7.4±.039 NS	0.90±0.296 *NS*	1.9 ±1.05 a	1.47±.070 a	65.8±9.13 *NS*	3.2±0.23 a	15.1±1.37 a
Distance from tree (0-10 cm)	1	7.3±.077	1.80± 0.401a	24.8±0.20	2.00±0.139 b	101.7±16.16	4.3±0.45	32.2±2.72 d
	2	7.2±.078	1.92± 0.317b	24.1±0.19	1.86±0.134 b	62.2±14.09	3.7±0.46	24.6±2.70 cd
	3	7.4±.076	1.72± 0.312b	23.6±0.20	1.81±0.134 b	55.6±13.32	3.4±0.45	20.4±2.70 bc
	M-1	7.5±.077	1.90± 0.421b	21.4±0.20	1.75±0.139 b	61.7±16.44	3.6±0.46	11.8±2.75 ab
	M	7.5±.077	1.97± 0.310b	23.9±0.19	1.66±0.130 ab	62.1±15.95	3.9±0.46	13.1±2.79 ab
	M+1	7.4±.076	2.00± 0.371b	21.4±0.20	1.68±0.132 ab	90.3±14.00	3.7±0.45	15.4±2.77 ab
	10-40 cm	7.5±.076 NS	2.65 ± 0.432b	19.4 ±0.21 *NS*	1.30±0.134 a	63.1±16.81 *NS*	3.6±0.45 *NS*	9.7±2.75 a

[a] GLM model. Values of F: * *P* <0.05; ** *P* < 0.01; *** *P* <0.001; NS: no significant differences; [b] EC in µS cm^{-1}. SOC in g kg^{-1}; TN mg g^{-1} soil, NO_3^- in mg kg^{-1} soil, NH_4^+- in mg kg^{-1} soil; Pavail in mg kg^{-1} soil; [c] Mean values for each measured parameter within main factors and with the same letter are not significantly different (P<0.05).; se: standard error.

Table 3. Effects of carbon treatments (CT), irrigation conditions (IC), and distance from the tree trunk (TD) and their interactions on exchangeable K (K exch), humic acids (HA), fulvic acids (FA), ratio of humic to fulvic acids (HA/FA), Soil Basal Microbial Respiration (SBMR), Microbial Biomass Carbon (MB-C), and metabolic quotient (qCO_2).

F value									
Source [(a)]		df	K exch	HA	FA	HA/FA	SBMR	MB-C	qCO_2
Carbon treatments (CT)		1	22.232***	0.132NS	33.171***	3.960*	0.759NS	0.292NS	0.731NS
Irrigation conditions (IC)		1	14.262***	42.428***	24.378***	28.222***	23.861***	29.933***	29.949***
Distance from tree (TD)		6	5.793***	0.331NS	4.265***	0.088NS	0.048NS	3.416**	0.299NS
CT x IC		6	2.598 NS	1.108NS	19.315***	0.743NS	1.956NS	0.017 NS	2.015NS
CT x TD		1	0.833NS	0.046NS	0.348NS	0.194NS	0.271NS	0.153NS	0.335NS
IC x TD		6	0.096NS	0.024NS	0.197NS	0.076NS	0.191NS	0.239NS	0.335NS
CT x IC x TD		1	0.168NS	0.029NS	0.484NS	0.230NS	0.099NS	0.046NS	0.286NS
Mean values ± se [(c)]									
Main factor			K exch [(b)]	HA [(b)]	FA [(b)]	HA/FA	SBMR [(b)]	MB-C [(b)]	qCO_2
Carbon treatments	Control		0.88±0.037b	2.11±0.139	1.15±0.030 b	0.71±0.025 b	0.333±.033	0.746±0.029	1.919±0.309
	Carbon inputs		0.63±0.037 a	2.04±0.140 *NS*	0.90±0.027 a	0.64±0.025 a	0.374±.034 *NS*	0.723±0.029 *NS*	2.295±0.314 *NS*
Irrigation conditions	Irrigated soil		0.85±0.039 b	2.71±0.147 b	1.13±0.032 b	0.58±0.026 a	0.470±.035 b	0.622±0.030 a	3.312±0.326 b
	Rainfed soil		0.68±0.035 a	1.43±0.132 a	0.92±0.029 a	0.77±0.024 b	0.238±.032 a	0.847±0.028 b	0.902±0.296 a
Distance from tree (0-10 cm)	1		0.96±0.069 c	2.25±0.262	1.17±0.057b	0.69±0.048.	0.360±.063	0.856±0.055 c	1.881±0.584
	2		0.97±0.069 c	2.15±0.260	1.11±0.056b	0.69±0.047.	0.359±.063	0.842±0.054 bc	2.040±0.579
	3		0.80±0.069 bc	2.14±0.250	1.08±0.054b	0.69±0.047	0.353±.063	0.794±0.055 bc	1.803±0.586
	M-1		0.63±0.070 ab	2.06±0.267	1.00±0.052b	0.68±0.043	0.369±.063	0.716±0.054 abc	2.007±0.586
	M		0.64±0.071 ab	2.06±0.261	1.01±0.059b	0.68±0.043	0.363±.063	0.678±0.054 ab	2.103±0.579
	M+1		0.71±0.070 ab	2.08±0.240	1.00±0.051 b	0.65±0.041	0.344±.063	0.677±0.054 ab	2.134±0.579
	10-40 cm		0.55±0.069 a	1.77±0.230 *NS*	0.80±0.056 a	0.67±.042 *NS*	0.328±.063 *NS*	0.579±0.055 a	2.782±0.586 *NS*

[(a)] GLM model. Values of F: * *P* <0.05; ** *P* < 0.01; *** *P* <0.001; NS: no significant differences; [(b)] K exch in $cmol_c$ kg^{-1} soil, HA and FA in mg g^{-1} soil, SBMR in CO_2–C kg^{-1} soil h^{-1}, BM-C in mg C kg^{-1} soil; qCO_2 in mg CO_2–C kg^{-1} MB-C h^{-1}; [(c)] Mean values for each measured parameter within main factors and with the same letter are not significantly different (P<0.05); se: standard error.