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Effects on soil organic matter mineralization and microbiological properties of applying compost to burned and unburned soils

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ABSTRACT

This study was undertaken in the context of a project of reclamation of a burned forest area applying municipal waste compost (MWC) and it consisted of an incubation experience carried out under laboratory conditions. The objectives of this research were to asses the effect of three doses of MWC added to burned and unburned calcareous soils on a) SOM mineralization and b) soil microbiological parameters. The laboratory incubation experience was carried out with three compost doses (1, 2 and 4% w/w) on a burned soil and another unburned one from an adjacent plot, besides the corresponding control samples. The mineralization kinetics of the organic matter was studied for 92 days. The kinetics data were adjusted to a double exponential model, showing two C pools of different degrees of resistance to mineralization and concentration, with half-life times of 1.9–4.9 and 34–76 days, respectively.

In the unburned soil, the initial potential mineralization rate of the labile and stable C pools showed an opposed behavior, increased and decreased with the MWC dose, respectively. However in the burned soil no significant tendencies were observed. Although applying compost tended to increase the size of more labile pool with respect to total mineralizable C, however most of the soil or compost OM did not result mineralizable in the short and medium term. The compost amendment did not increase soil microbial activity.

1. Introduction

Soil organic matter (SOM) is universally recognized to be among the most important factors responsible for soil fertility, crop production, and land protection from contamination, degradation, erosion and desertification, especially in semiarid and arid areas (Senesi et al., 2007). Forest fire is considered the main disturbance in Mediterranean areas (Whelan, 1995) and constitutes a serious environmental problem, due to the destruction of vegetation and also because of the soil degradation (Hernández et al., 1997; Guerrero et al., 2001; Turrión et al., 2010). Fire can consume part or all of the standing plant material and litter, as well as the SOM in the surface horizons (Guerrero et al., 2001). The loss of organic matter (OM) through fire, as well as the effect of fire on microbiota and the decrease in vegetation and soil cover, will favor surface soil erosion, particularly in Mediterranean forests, causing alterations in biological cycling of nutrients (Prichett and Fisher, 1987; Hernández et al., 1997). In recent years, the need to protect soils from degradation and/or erosion has spurred a series of efforts to find alternative practices aimed at restoring and/or improving SOM content and functions. As a result, recycling large amounts of organic residues, by-products, wastes and effluents (such as municipal sewage sludges and urban solid wastes, food industry and wood processing wastes, agricultural crop residues and animal wastes) as soil organic amendments has become a very popular and efficient agricultural practice (Senesi, 1989; Senesi et al., 2007). Increasing SOM content also enhances soil quality, reduces soil erosion (Guerrero et al., 2001), improves water quality, increases biomass and agronomic productivity and improves environmental quality by adsorbing pollutants from natural waters and reducing atmospheric CO_2 concentration (Lal and Kimble, 1999).

Applying organic wastes to soil could represent a useful tool in maintaining and increasing amounts of SOM (Mondini et al., 2007). Effective recycling of organic residues in soil requires the optimization of soil and organic waste management in order to minimize CO_2 emissions and optimize soil C sequestration efficiency. Most studies, however, have been conducted for evaluating the effects

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of organic amendments on total and available amounts of nutrient elements added to soil, of the danger of phytotoxicity to crops, of potential modifications of soil microbial populations and of activities and effects of toxic trace metals and organic chemicals on crops and waters (Mondini et al., 2007). In contrast, relatively little attention has been applied to study the effects that organic amendments may exert on stabilization of soil organic matter and chemical status, environmental role and fertility functions of the soil humic substances (Senesi et al., 2007).

From an environmental point of view, correct management of the exogenous OM addition to soil relies on two main aspects: efficient SOM increase and adequate match of the release of mineral nutrients to plant demand. Therefore, knowledge of C mineralization dynamics in amended soils is of intrinsic interest. Using laboratory methods involving incubation of soil-waste mixtures under controlled conditions can supply accurate information about C mineralization dynamics (Fernández et al., 2007) and efficiency of soil C sink (Mondini et al., 2007). Rates of organic matter decomposition depend upon type of organic amendment and soil properties, so exogenous material added to burned and to unburned soils could be expected to behave differently. Soil microorganisms play an important role in the decomposition of organic matter acting as agents in nutrient cycling and energy flow, and they are extremely sensitive to environmental changes (Vázquez et al., 1993).

This study was an incubation assay carried out under laboratory conditions and it was undertaken in the context of a project of reclamation of a burned forest area that includes a field experience of soil recovery using municipal waste compost (MWC, Olalla et al., 2008). The objectives of this research were to asses the effect of three doses of MWC added to burned and unburned calcareous soils on a) SOM mineralization and b) soil microbiological parameters.

2. Material and methods

2.1. Location

The study area, called *Monte de la Abadesa* (42°19′14″ N y 3°41′11″ W), is located at 897 m above sea level in a calcareous moor next to Burgos city in the region of *Castilla y León* (Northwest Spain). Mean annual rainfall is 564 mm and mean annual temperature is 10.5 °C. Soils are *leptic Cambisols* (*eutric*) over calcareous bedrock (IUSS Working Group WRB, 2006). The area was forested during the 60's with *Pinus sylvestris* Mill. and *Pinus pinaster* Aiton, and was burned in October 2004. Fire severity (Pausas et al., 2003) can be considered as moderate, consumption of litter layer could be observed, but no visible alteration of the mineral soil surface. The fire affected only a part of the forested area. At present, unburned and burned forests coexist in adjacent plots.

2.2. Soil sampling and incubation experiments

Soil sampling was performed in April 2006, eighteen months after fire. For laboratory incubation experience, 0–5 cm depth soil samples from the burned and unburned areas were used, obtaining a composite sample from each area by mixing five samples. Soil texture was sandy clay loam with a 26.4% of clay. The burned and unburned points of sampling were 100 m away each other. Visible plant residues and roots were removed and soil samples were sieved (<2 mm). For soil and MWC characterization, pH, electric conductivity, total N, total C, carbonate and organic C (SOC) and SOC/N were determined. Total concentrations of soil C and N were determined in an automated C/N analyzer (CHN-2000, Leco). Organic carbon was calculated as the difference between total and carbonate C. Soil total carbonates were determined using 1 M HCl titrated with 0.5 M NaOH (FAO, 2007). Some properties of the materials used for the mineralization assay are shown in Table 1.

Table 1
Some properties of the materials used in the incubation assay.

	pH	EC	Carbonates	SOC	N	SOC/N
		[mS cm^{-1}]	[gCaCO$_3$ kg^{-1}]	[g kg^{-1}]		
UBS	5.8	0.305	17	108	3.1	35
BS	7.4	0.380	54	53.8	2.6	21
MWC	8.0	15.4	192	187	9.3	20

Note: UBS: unburnt soil; BS: burnt soil, MWC: municipal waste compost, EC: electric conductivity SOC: soil organic carbon, N: total nitrogen.

Three compost (MWC) doses were added to each soil sample (1, 2, and 4% dry weight); control and compost samples were used as well. Soil samples (50 g of soil sieved by 2.0 mm) were thoroughly mixed with 0.50 g, 1.0 g or 2.0 g of MWC (sieved by 2 mm), and for MWC incubation an amount of 50 g was also used. Compost doses were chosen in accordance with a parallel field experience of reclamation (Olalla et al., 2008) and they were equivalent to 15, 30 and 60 Mg ha^{-1} (for 10 cm of soil depth), which can be considered usual organic amendment doses (Kaschl et al., 2002; Pedra et al., 2007; Barral et al., 2009). Five replicates were considered, obtaining 45 samples for the mineralization assay and microbiological analysis.

2.3. C mineralization

C mineralization was determined according to Isermayer (1952) in closed chambers and under laboratory-controlled conditions. Each sample was analyzed in five parallel incubations. Dry samples were wetted to 75% of water holding capacity and incubated in 1 L jars at 29 °C for 92 days. The moisture content was kept constant by weighing at each sampling date. The CO$_2$ evolved was collected, after 2, 6, 9, 12, 15, 19, 22, 26, 29, 34, 40, 44, 48, 51, 54, 61, 68, 75, 81 and 92 days of incubation, in 10 ml 0.5 M NaOH and determined by titration with 0.5 M against a phenolphthalein indicator after precipitation with BaCl$_2$ (0.5 M). The quantities and rates of labile and stable C mineralized during the course of the incubation were calculated by fitting the cumulative CO$_2$–C curves to the double exponential model (Andrén and Pauskian, 1987). This model separates the mineralizable organic C into active and slow pools and can be presented as

$$C_m = C_1\left(1 - e^{-k_1 t}\right) + C_2\left(1 - e^{-k_2 t}\right) \quad [1]$$

where C_m is the known cumulative amount of C respired at sampling period t; C_1 and C_2 are the sizes of the active and slow pools of mineralizable C, respectively; and k_1 and k_2 are the corresponding mineralization rate constants for each pool.

2.4. Microbiological analyses

Microbial biomass C (MBC) was determined by the chloroform fumigation extraction method, using 0.5 M K$_2$SO$_4$ as extractant (Vance et al., 1987) after 92 days of incubation. C contents in the fumigated and non-fumigated extracts were determined using an SKALAR FormacsHT Total Organic Carbon (TOC) analyzer for liquid samples.

The total respiration in 92 days ($C_{\mathrm{min\ 92d}}$) was determined. The metabolic quotient ($q_{\mathrm{CO_2}}$) represents the respiration per mass unit of microbial biomass C, and was calculated as reported by Anderson and Domsch (1993). The microbial quotient (MBC/SOC) represented the fraction of MBC with respect to SOC (Anderson and Domsch, 1993).

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2.5. Statistical analyses

The STATISTICA 7.0 software package was used to apply an ANOVA to test the effect of compost amendments after verifying normal distribution with the Kolmogorov–Smirnov test and variance homogeneity of residual with the Levene test. The factor considered was compost dose at four levels (control, dose 1, dose 2 and dose 3). The ANOVA was performed for both fire regimes separately (burned and unburned). When there were significant effects, means were compared using the Bonferroni test at level $p < 0.05$. A polynomial contrast (first and second degree) was carried out to ascertain the tendency with the increase of compost doses for each parameter studied.

3. Results and discussion

3.1. C mineralization

For soils, compost, and soils amended with compost, the accumulated amount of organic C mineralized was fitted to a double exponential model (Equation (1)) with high determination coefficients ($r^2 > 0.999$). This model appears to be consistent with some mechanistic models that divide soil organic matter into active, slow and resistant pools (or other synonyms) with different mineralization rates (Jenkinson, 1977; Kätterer et al., 1998). The resistant pool is not included in the equation, assuming that it does not contribute significantly to C mineralization in a relatively short period (Wang et al., 2004). In their study on utilization of MSW compost for organic matter conservation in agricultural soils in Northwestern Spain, Barral et al. (2009) found that a simple first-order kinetic model described compost mineralization adequately, whereas soil mineralization and soil amendment were best described by a two-compartment first-order model. Table 2 shows the model parameters obtained in the present study from the regression of the C–CO_2 emission data, the half-life times and the initial potential rates of C mineralization ($C_n \times k_n$) for each pool, and the percentage of C active pool (C_1) with respect to total mineralizable C.

The mineralization rates of the labile organic pool (k_1) showed values between 0.15 and 0.36 d^{-1} and this pool had half-life times of 1.9–4.9 d. The k_1 values were higher than those obtained by Bernal et al. (1998), but closer to those found by Pedra et al. (2007). The C_1 values for the control soils were higher than those obtained by Pedra et al. (2007) for a *Haplic Podzol* and a *Calcic Vertisol,* but the values were similar for the amended soils. Our results showed that the initial potential rate of C mineralization and the half-life times for the active or labile C pool, for burned and unburned soils, were similar suggesting that, in both soils, this pool presents organic compounds of similar decomposability.

The low values obtained for the percentage (% C_1) of the more active pool relative to total mineralizable C ($C_1 + C_2$) showed that a small part of SOC has a half-life time of only few days. Some authors have indicated that an initial mineralization flush is produced by the sample handling (drying, rewetting, etc.) in mineralization studies and that it corresponds to the active pool that appears in the equation (Molina et al., 1980). The % C_1 was higher in the burned soil than in the unburned, which could be related to the modification of the soil conditions that can favor microbiota development, such as high soil pH and increase in nutrient availability, as can be seen in Table 1 (Marion et al., 1981; Prieto-Fernández et al., 1993; Fernández et al., 1999). As can be seen in supplementary material (Table 3), in unburned soils, k_1 showed a significant linear tendency to decrease with the MWC dose, whereas half-life time of the labile C pool had a significantly quadratic tendency to increase with the MWC dose. In the burned soil not significant tendencies were observed for these parameters. For C_1 in both soils (burned and unburned) the tendency was to increase with the increment of MWC addition.

For the mineralization of the stable C pool, which mainly consisted of compounds more resistant to microbial attack that broke down slowly during a second mineralization phase, the mineralization rate values varied between 0.009 and 0.020 d^{-1} and the half-life times between 34 and 76 d (Table 2). The compost mineralization showed intermediate values between the two studied soils for these parameters (k_2 and C_2). Bernal et al. (1998) found that more than 88% of TOC in mature compost added to calcareous silt loam soil was slowly mineralizable with rate constants ranging from 0.0030 to 0.0010 d^{-1}, which is very similar to the mineralization rates obtained in the present study.

The mineralization rates of the stable pool (k_2) and concentrations of this pool (C_2) were higher in the unburned soil than in the burned one. During the second phase of mineralization, the burned soil SOM was more stable than that of the unburned soil, as is reflected by the lower $C_2 \times k_2$ product and the longer half-life time of C_2 in the burnt soil. These results indicate that the burnt soil SOM shows lower decomposability than that of the unburned (González-Pérez et al., 2004). Several researchers have suggested that the product $C_n \times k_n$ (initial potential mineralization rate) is more accurate to explain and understand SOM quality than either one separately (Fernández et al., 2007).

The half-life time of the stable mineralizable C pool showed no significant differences among doses in both soils (unburned and burned). The initial potential mineralization rate of the stable pool

Table 2
Mineralization rate constants (k_1 y k_2), labile and stable C pool concentrations (C_1, C_2), half-life time of the labile and stable pools ($t_{1/2}\ C_1$ and $t_{1/2}\ C_2$), initial potential rate ($C_1 \times k_1$, $C_2 \times k_2$), percentage of labile *C* with respect to total mineralizable C ($C_1 + C_2$) and microbiological parameters for compost, unburned and burned soils.

	C_1	C_2	% C_1	k_1	k_2	$t_{1/2}\ C_1$	$t_{1/2}\ C_2$	$C_1 \times k_1$	$C_2 \times k_2$	MBC	$C_{min\ 92d}$	MBC/SOC	q_{co_2}
	[g C kg^{-1} soil]			[day^{-1}]		[day]		[g kg^{-1} day^{-1}]		[g C kg^{-1} soil]		[gC_{mic} kg^{-1}SOC]	[gC_{min92d} g^{-1}MBC]
MWC	1.85	24.2	6.4	0.19	0.013	3.5	54.3	0.339	0.309	6.97	17.85	55.0	2.56
UBS	0.51b	12.4a	4.0b	0.36a	0.016b	1.9b	42.3a	0.198a	0.203a	1.51a	10.15a	14.8a	7.67a
UBSC1	0.47b	12.0a	4.0b	0.35a	0.018b	2.1b	38.2a	0.164b	0.218a	1.42a	10.15a	14.4a	7.37a
UBSC2	0.76b	10.0b	6.5b	0.30a	0.020a	2.6b	34.1a	0.185b	0.204a	1.49a	9.13b	15.1a	6.18 ab
UBSC3	1.47a	10.3b	12.4a	0.15b	0.016b	4.9a	42.4a	0.209a	0.169b	1.72a	9.43b	17.1a	5.30b
BS	0.82b	7.03a	11.0b	0.24a	0.010a	2.9a	75.8a	0.196a	0.062a	1.18a	4.65a	24.1a	3.99a
BSC1	1.05a	5.75b	15.3a	0.16b	0.009a	4.1a	75.5a	0.161a	0.054a	1.03 ab	4.66a	19.6 ab	4.81a
BSC2	1.08a	5.12c	15.5a	0.18b	0.011a	4.1a	63.2a	0.203a	0.058a	1.09 ab	4.40a	21.5 ab	4.11a
BSC3	1.08a	5.59bc	16.1a	0.18b	0.011a	3.8a	66.2a	0.196a	0.061a	0.80b	4.68a	16.2b	5.50a

Note: MBC: microbial biomass C; $C_{min\ 92d}$: basal respiration after 92 days of incubation; q_{CO2}: metabolic quotient. MWC: municipal waste compost; UBS: unburned soil; BS: burned soil. Values in one column followed by the same letter are not significantly different ($p < 0.05$) among doses within the same material (burned or unburned) with the Bonferroni test.

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was significantly lower for the highest dose than for the others in the unburned soil, and as can be seen in supplementary material (Table 3) the tendency was to decrease with the MWC dose increase, probably due to an inhibitor effect (Borken et al., 2002); there were no significant differences in burned soils. The decrease observed in the amount of C mineralized in samples with added compost would be consistent with that established by Blagodstkaya and Kurzyakov (2008), who determined that substrate additions to the soil such that the rate of added C with respect to microbial biomass C exceed 200–500% cause a priming effect (short-term change in the turnover of soil organic matter) that tends towards zero and can be negative. Considering that MBC usually varies in 1–5% range of total organic C (Alef and Nannipieri, 1995), and it varied between 1.5 and 2.4% in our results (Table 2), the added compost doses exceed those rates. Mechanisms for this effect may be different and simultaneous (Blagodstkaya and Kurzyakov, 2008): changes in microbial community structure, preferential microbial substrate utilization, demand for other nutrients (such as N), etc.

The incubation assay of compost samples showed that the mineralizable C ($C_1 + C_2$) was only 14% of MWC C, so a large amount of added C was in recalcitrant forms. The low biodegradation rate of compost in the incubation experiment might thus suggest that these materials really contribute to long-term accumulation of OM in soil. Ribeiro et al. (2010) indicated that the addition of three different combinations of hen manure and stabilized compost to a *Cambic Arenosol* promoted an initial faster mineralization of the OM and consequently a faster release of nutrients, without affecting the total amount of C sequestered in soil.

3.2. Microbiological and biochemical parameters

Microbial biomass C reflects the size of the soil microbial community and basal respiration reflects the activity of this biomass (Nannipieri et al., 1990). Our results showed similar values of MBC for the soils studied and lower values of $C_{\mathrm{min}\ 92\mathrm{d}}$ in the burned control soil than the unburned one (Table 2). Compost addition showed significant decrease on MBC for burnt soil with the highest dose and significant decrease on $C_{\mathrm{min}\ 92\mathrm{d}}$ for unburnt soil with dose 2 and 3 (Table 2). Calbrix et al. (2007) did not observe significant differences on MBC after amending a cultivated soil with three types of organic materials (sewage sludge, turkey manure and compost made of turkey manure and ligneous waste); the absence of influence was justified by the use of organic amendment levels no higher than normal recommendations and by the assay with a single soil type and over a short length of time. Generally, compost additions cause a significant increase in soil respiration and soil microbial biomass carbon in relation to the control (Pedra et al., 2007; Tejada et al., 2009). These increases are attributed to the incorporation of easily degradable organic C, which stimulates the zymogenous microbial activity of the soil (Bernal et al., 1998; Stemmer et al., 2000) and to the incorporation of exogenous microorganisms (Blagodatsky et al., 2000). However, some authors (Borken et al., 2002) observed a reduction in microbial biomass following compost treatment of degraded temperate forest soils, suggesting that the initial salt content of the compost could have contributed to the decline in the original microbial biomass.

The MBC/SOC quotient has been used by many authors as an indicator of changes in SOM (Hernández et al., 1997). The metabolic quotient (q_{co_2}) is an index of microbial efficiency in the utilization of C resources and greater efficiency results in a low metabolic quotient (Anderson, 2003). This parameter has been successfully used to detect disturbance or stress of the soil microbial biomass due to external inputs of organic matter (Anderson and Domsch, 1993) or the presence of toxic substances such as heavy metals (Brookes and McGrath, 1984), which were usually reflected as an increase of q_{co_2}. Killham (1985) suggested that microbial biomass under stress diverts more energy from growth into maintenance, so an increased proportion of carbon taken up by the biomass is respired as CO_2.

The burned control soil showed lower q_{co_2} and larger MBC/SOC than the unburned control soil, suggesting that microbial communities in burned soils were more efficient in C use than communities in unburned soil. The effect of compost addition on the microbiological parameters studied was different in the burned and unburned soil as can be seen in supplementary material (Table 3), where significant polynomial contrast and different tendency with the MWC dose are showed. The MBC/SOC quotient showed a non-significant increase with the compost dose in the unburned soil, and a significant linear decrease in the burned soil supplementary material (Table 3). In the unburned soil, a significant increase in metabolic efficiency was observed with the increase of compost dose; however, no significant differences among doses were observed in the burned soil (Table 2), but the tendency to linear increase of the metabolic quotient with the MWC dose was significant in this soil supplementary material (Table 3). These different effects of compost amendment on microorganisms depended on the soil characteristics. These findings are in agreement with those reported by Bernal et al. (1998) who found, in an incubation experiment of soil amended with compost with different stabilization degrees, more efficient C conservation with mature compost.

4. Conclusions

Many of the parameters studied showed different tendencies with compost addition when the amendment was applied to burned or unburned soil. For the unburned soil, compost tended to decrease the initial potential mineralization rate in the stable SOM pool and to increase it in the labile SOM pool. However, it showed no significant effects on these pools in the burned soil. Adding compost tended to increase the size of more labile pool with respect to total mineralizable C ($C_1 + C_2$).

The compost amendment carried out did not increase soil microbiological activity, which even decreased in some cases. Most of the soil or compost OM did not result mineralizable in the short and medium term. For these soils and this compost, it could be considered that additions such as those tested may contribute to increasing long-term SOM levels. What is more, from this perspective, compost application constitutes an interesting option for sequestering C in soil. Behavioral differences of different composts and different soils require further investigation to obtain more advanced models that, integrating soil and compost features and conditions, facilitate making reasonable forecasts on OM evolution.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.jenvman.2010.10.020.

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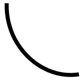
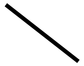
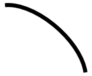
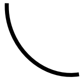
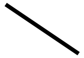
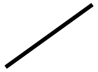
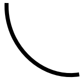
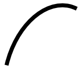
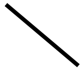
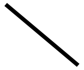
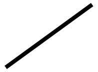
Table 3. Significance of the polynomial contrast and tendency with the increased compost dose of mineralization rate constants (k_1 y k_2), labile and stable C pool concentrations (C_1, C_2), half-life time of the labile and stable C pools ($t_{1/2}$ C_1 and $t_{1/2}$ C_2), initial potential rate (C_1*k_1, C_2*k_2), percentage of labile C with respect to total mineralizable C (C_1+C_2) and microbiological parameters for unburned and burned soil.

		C_1	**C_2**	**% C_1**	**k_1**	**k_2**	**$t_{1/2}$ C_1**	**$t_{1/2}$ C_2**	**C_1*k_1**	**C_2*k_2**	**MBC**	**$C_{min\ 92d}$**	**MBC/SOC**	**q_{CO2}**
UNBURNED	**1stdegree**	*** (+)	*** (-)	*** (+)	*** (-)	ns	*** (+)	ns	* (+)	*** (-)	ns	*** (-)	ns	** (-)
	2nd degree	** (+)	*** (+)	* (+)	ns	*** (-)	* (+)	ns	** (+)	** (-)	ns	** (+)	ns	ns
	Tendency													
BURNED	**1st degree**	* (+)	*** (-)	** (+)	ns	ns	ns	ns	ns	ns	** (-)	ns	** (-)	** (+)
	2nd degree	ns	*** (+)	* (-)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Tendency													

Note: MWC: municipal waste compost: UBS: unburned soil; BS: burned soil. *** $p< 0.001$; ** $p< 0.01$; * $p<0.05$; ns: no significant differences for the polynomial contrast. Signs in brackets indicate the tendency (+: increasing; -: decreasing).