Chapter 2
Organic Matter and Micro-Organisms in Tropical Soils

Rainer Georg Joergensen

2.1 Introduction

Organic matter and soil micro-organisms are key components for soil fertility, i.e., the ability of a soil to provide nutrients for plant growth, and for soil quality, i.e., the capacity of a soil to maintain key ecological functions such as decomposition of organic residues (Craswell and Lefroy 2001; Joergensen and Castillo 2001; Cerri et al. 2006). Soil micro-organisms encompass archaea, bacteria, fungi, and protozoa. They maintain the majority of enzymatic processes in soil and preserve energy and nutrients in their biomass (Jenkinson and Ladd 1981). The diversity of soil micro-organisms is enormous and the majority of species are still unknown, although microbial diversity has received much research interest over the past decade (Torsvik and Øvreås 2007).

The maintenance of soil fertility and soil quality is especially important in tropical regions (Bationo et al. 2007). Since temperature controls many processes in soil, especially those mediated by soil micro-organisms, the higher temperature in tropical regions leads to faster turnover rates of microbial biomass and soil organic matter in comparison to temperate climatic conditions (Jenkinson and Ayanaba 1977; Diels et al. 2004; see Chap. 1), shortening the time taken for ecosystems to respond to changes in management practices and increasing the risk of permanent damage (Cerri et al. 2003). In contrast to the nearly constant air temperature, humidity and soil water content are characterized by extreme changes between dry and rainy seasons under tropical savannah (Gijsman et al. 1997; Andersson et al. 2004; Ndiaye et al. 2004) and tropical monsoon climatic conditions (Srivastava and Singh 1991; Manna et al. 2007; Vineela et al. 2008).

R. Georg Joergensen
Department of Soil Biology and Plant Nutrition, University of Kassel, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany
e-mail: joerge@uni-kassel.de

P. Dion (ed.), *Soil Biology and Agriculture in the Tropics*, Soil Biology 21,
DOI 10.1007/978-3-642-05076-3_2, © Springer-Verlag Berlin Heidelberg 2010

Only under equatorial rainforest climatic conditions is microbial activity not limited throughout the year by humidity and soil water content (Henrot and Robertson 1994; Cleveland et al. 2003; Li et al. 2006a,b). Tropical equatorial rainforests have been subjected to heavy logging and agricultural clearance throughout the twentieth century and up to the present day, and the area covered by rainforests around the world is rapidly shrinking (Luizao et al. 1992; Henrot and Robertson 1994; Adachi et al. 2006). In these equatorial areas, agricultural land-use systems are new and may not be sustainable (Motavalli et al. 2000; Dinesh et al. 2003; Bossio et al. 2005). In other tropical regions, especially those with tropical monsoon climatic (Witt et al. 2000) conditions, sustainable agricultural land-use systems have existed for several hundreds of years.

Human impact on soil micro-organisms by changes in land use may lead to adverse effects on soil processes, which is the driving force behind many research activities. Important and typical research objectives have been land-use conversion (Ayanaba et al. 1976; Luizao et al. 1992; Basu and Behera 1993; Prasad et al. 1995; Gijsman et al. 1997; Motavalli et al. 2000; Dinesh et al. 2004a; Bossio et al. 2005; Nogueira et al. 2006), crop rotation (Wick et al. 1998; Oberson et al. 2001; Bünemann et al. 2004; Izquierdo et al. 2003; Adeboye et al. 2006; Vineela et al. 2008), tillage (Salinas-García et al. 2002; Balota et al. 2004; Agele et al. 2005), agroforestry (Mazzarino et al. 1993; Tornquist et al. 1999; Marschner et al. 2002), and conversion of rainforest to plantation (Behera and Sahani 2003; Dinesh et al. 2003; Adachi et al. 2006).

The variability of soils is much higher in tropical regions than in the Luvisol- and Cambisol-dominated landscape of temperate regions. The range of tropical soils goes from young and nutrient rich volcanic Andisols (Joergensen and Castillo 2001; Rabary et al. 2008) to Oxisols (Zhang and Zhang 2003; Bünemann et al. 2004; Xu et al. 2007), Ultisols (Haron et al. 1998; Cantarutti et al. 2002; Cerri et al. 2003) and old landscapes devoid of nutrients after elution by tropical rainfall for millions of years. This variability may mask damage to important soil functions. In addition, the habitat soil needs long periods not only for formation, but also for recovery and restoration. In contrast, soil organisms are generally recognized as highly dynamic, reacting rapidly to environmental conditions (Winding et al. 2005; Bastida et al. 2008). It has been reported that microbial biomass sensitively indicates changes due to soil management, long before other parameters such as soil organic C or total nitrogen (Powlson et al. 1987). Knowledge about soil micro-organisms and soil biological processes may improve the scientific basis of management decisions, e.g., determination of the type of species to be used for planting and cropping in tropical areas.

The aim of the present review is to examine to what extent differences in tropical soil properties and land-use management affect soil organic matter, soil microbial biomass and microbial activity, particularly basal respiration, and modify the relationships between these elements. In preparing the current chapter, due consideration was given to the fact that our present knowledge on this subject is mainly derived from soils developed under temperate humid climatic conditions. After some methodological remarks, the progress of our knowledge on soil micro-organisms in

tropical soils is examined, as are the severe gaps in our understanding that need to be addressed by future research.

2.2 Methods Used in Preparation of the Present Review

2.2.1 Data Collection

Data were obtained from the literature for sites located in the tropics between latitude of 24°00′N and 23°40′S, with an altitude not exceeding 2,200 m elevation above sea level (ASL) and a mean annual temperature not falling below 15.3°C. This definition is somewhat arbitrary, as tropics and tropical climate have sometimes been defined differently. One site was considered as an independent sample, i.e., the results of different plots in short-term and small-scale field experiments were combined to obtain one average value (Wick et al. 1998; Balota et al. 2004; Adeboye et al. 2006). Also, the results of different sampling dates throughout the year were averaged to one value (Basu and Behera 1993; Behera and Sahani 2003; Cleveland et al. 2003), as the present review is not focused on seasonal variations of the microbial biomass. Strong seasonal variations of the soil organic C and total N content indicate the occurrence of nondetected spatial variability (Basu and Behera 1993; Sahani and Behera 2001; Saynes et al. 2005; Galicia and García-Oliva 2008).

Basic requirements for including the data in the present review were information on the location of sampling and on the contents of microbial biomass C and soil organic C in μg g^{-1} soil. Data presented on a per area basis (g m^{-2} or kg ha^{-1}) were recalculated into the respective contents if bulk densities were provided (Cerri et al. 2003; Saynes et al. 2005; Li et al. 2006a). Other soil data collected from the references were soil pH, contents of clay, sand, total N, total P, microbial biomass N, microbial biomass P, basal respiration, ergosterol, ATP, and soil type (USDA classification system). Soils classified according to the WRB-FAO classification system were converted to the USDA classification system (see Chap. 1 for further information on the USDA and WRB classification systems).

Information on land-use systems, mean annual temperature, mean annual precipitation and were collected as important environmental variables. If latitude and ASL were not presented in a particular reference, these data were obtained from Google Earth. Also, data on mean annual temperature and mean annual precipitation were obtained from the Internet if not provided by the respective reference. All sites were separated into four classes according to their land-use management: (1) arable (Table 2.1), (2) plantation (Table 2.2), (3) pasture (Table 2.3), and (4) forest sites (Table 2.4). Plantation sites include agroforestry sites. Pasture sites include meadows, grass savannah, tree savannah, and fallow sites. Forest sites include natural primary and secondary forest sites.

Table 2.1 Arable soils of the tropics: basic parameters and carbon-related microbial properties

Reference, number of sites	Latitude	ASL (m)	Temperature (°C)	Rainfall (mm)	pH (H_2O)	Total N (mg g^{-1} soil)	Microbial biomass C (μg g^{-1} soil)	Microbial biomass C/soil organic C (%)
Islam and Weil (2000), 1	24°00′N	20	26.0	1,800	5.3	0.8	160	2.1
Srivastava and Singh (1991), 1	23°45′N	360	26.5	1,040	6.7	1.1	250	2.3
Shen et al. (2001), 5	23°08′N	10	21.5	1,680	4.5	0.7	290	3.7
Izquierdo et al. (2003), 1	23°02′N	30	24.6	1,300	5.7	3.0	450	2.2
Manna et al. (2007), 6	22°41′N	310	25.5	830	8.1	0.5	310	5.9
Tripathi et al. (2006), 9	22°15′N	3	22.1	1,900	6.2	ND	290	3.0
Bhattacharyya et al. (2005), 1	22°02′N	10	26.5	1,600	5.5	1.7	180	1.3
Das et al. (2007), 2	21°51′N	10	26.5	1,715	7.2	0.9	320	3.2
Prasad et al. (1995), 1	21°22′N	150	25.0	1,400	6.7	1.3	310	2.4
Basu and Behera (1993), 1	19°59′N	260	24.0	1,500	6.7	3.2	350	1.1
Zhang and Zhang (2003), 1	19°31′N	150	23.3	1,830	4.9	ND	220	2.3
Ndiaye et al. (2004), 1	14°47′N	70	26.2	440	ND	0.5	50	0.8
Villenave et al. (2004), 1	14°41′N	20	26.2	460	6.9	0.6	70	0.8
Ndour et al. (2008), 2	14°41′N	20	26.2	460	6.5	1.0	100	1.2
Witt et al. (2000), 16	14°10′N	20	30.0	2,100	6.4	1.0	220[a,b]	2.1
Villenave et al. (2003), 2	13°47′N	20	26.2	440	5.3[c]	0.3	70	1.8
Sall et al. (2006), 1	13°45′N	10	26.2	650	5.5	0.3	50	0.9
Rajashekhara Rao and Siddaramappa (2008), 1	12°58′N	930	23.9	870	6.4	ND	80	1.8
Vineela et al. (2008), 4	12°58′N	930	23.8	920	5.5	ND	140	3.3
Joergensen and Castillo (2001), 25	12°04′N	50	28.5	1,800	6.5	1.5	120	0.7
Bilgo et al. (2007), 4	11°51′N	330	29.0	850	6.6[c]	0.3	42	1.1
Adeboye et al. (2006), 1	11°11′N	680	27.0	1,060	5.7	0.7	260[b]	4.5
Mazzarino et al. (1993), 1	9°53′N	600	22.0	2,640	5.0	2.6	130[a,b]	0.3
Lulu and Insam (2000a, b), 13	9°01′N	2200	16.5	1,110	6.6	1.9	320	1.7
Wick et al. (1998), 3	7°30′N	210	26.2	1,250	6.2	0.5	120	2.2
Ayanaba et al. (1976), 12	7°23′N	210	26.5	1,120	6.4	0.9	190	1.8

Mulongoy (1986), 1	7°23′N	210	26.5	1,300	5.6	1.9	170	1.0
Tian (1998), 1	7°23′N	210	26.5	1,300	5.8	ND	240	2.4
Agele et al. (2005), 1	7°05′N	270	26.2	1,250	6.7	2.7	370[a]	1.1
Oberson et al. (2001), 1	4°30′N	150	27.0	2,240	4.7	1.7	160[a,b,d]	0.6
Gijsman et al. (1997), 5	4°00′N	200	27.0	2,200	4.4	1.3	450[a,b]	1.5
Bünemann et al. (2004), 4	0°09′N	1480	18.0	960	5.0	1.8	280[d]	1.1
Bossio et al. (2005), 7	0°02′N	1540	18.5	1,700	5.1	ND	160[a]	0.8
Rabary et al. (2008), 4	19°46′S	1600	16.9	1,450	5.7	3.8	340	0.7
Fernandes et al. (2005), 2	22°47′S	570	22.0	1,430	5.8	1.1	140[a,b]	0.9
Nogueira et al. (2006), 4	23°27′S	580	20.9	1,620	6.0[c]	ND	660[a]	2.7
Balota et al. (2004), 6	23°40′S	580	22.4	1,990	4.6	ND	234	1.4

Sequentially shown are: reference, number of sites analyzed, site parameters (latitude, elevation above sea level (ASL), mean annual temperature, mean annual rainfall), soil pH, soil total N, soil microbial biomass C, soil microbial biomass C/soil organic C ratio; *ND* not determined

[a]corrected k_{EC} value

[b]corrected k_{EN} value

[c]adjusted soil pH

[d]corrected k_{EP} value

Table 2.2 Plantation soils of the tropics: basic parameters and carbon-related microbial properties

Reference, number of sites	Latitude	ASL (m)	Temperature (°C)	Rainfall (mm)	pH (H_2O)	Total N (mg g^{-1} soil)	Microbial biomass C (μg g^{-1} soil)	Microbial biomass C/soil organic C (%)
Xu et al. (2007), 1	21°56′N	720	22.0	1,400	4.6	1.0	230	2.3
Zhang and Zhang (2003), 3	19°31′N	150	23.3	1,830	4.5	ND	180	1.9
Zhang et al. (2007), 2	19°28′N	150	23.3	1,830	4.5	0.7	200	2.0
Templer et al. (2005), 1	19°00′N	50	25.2	2,000	5.5	ND	1,510[a,b]	1.9
Dinesh et al. (2003), 4	11°37′N	40	30.1	3,100	5.1	0.8	160	2.2
Dinesh (2004), 5	11°37′N	40	30.1	3,100	5.2	0.7	290	3.9
Dinesh et al. (2004a), 5	11°37′N	40	30.1	3,100	5.9[e]	1.3	390	2.9[d]
Dinesh et al. (2004b), 3	11°37′N	40	30.1	3,100	5.8[e]	0.9	190	2.2
Tornquist et al. (1999), 1	10°26′N	40	26.5	3,910	4.8	3.7	1,260[a,b]	3.4
Adachi et al. (2006), 1	2°50′N	20	27.5	1,900	4.7[e]	1.2	80	0.5
Haron et al. (1998), 3	1°02′N	50	27.0	2,000	4.4	1.4	260	1.5
Bossio et al. (2005), 1	0°02′N	1540	18.5	1,700	4.1	ND	290[c]	1.0
Förster et al. (2006), 1	3°07′S	90	26.9	2,000	4.0	2.1	220	0.8
Marschner et al. (2002), 2	3°08′S	50	25.8	2,530	4.3	ND	480[c]	1.6
Turgay et al. (2002), 4	5°08′S	650	24.0	1,750	5.3	2.6	660	2.1
Waldrop et al. (2000), 4	17°30′S	270	26.0	1,730	4.1	1.9	220	0.6

Sequentially shown are: reference, number of sites analyzed, site parameters (latitude, elevation ASL, mean annual temperature, mean annual rainfall), soil pH, soil total N, soil microbial biomass C, soil microbial biomass C/soil organic C ratio; *ND* not determined

[a]corrected k_C value

[b]corrected k_N value

[c]corrected k_{EC} value

[d]corrected soil organic C content

[e]adjusted soil pH

Table 2.3 Savannah soils of the tropics: basic parameters and carbon-related microbial properties

Reference, number of sites	Latitude	ASL (m)	Temperature (°C)	Rainfall (mm)	pH (H_2O)	Total N (mg g^{-1} soil)	Microbial biomass C (μg g^{-1} soil)	Microbial biomass C/soil organic C (%)
Islam and Weil (2000), 1	24°00′N	20	26.0	1,800	5.6	1.1	390	3.1
Srivastava and Singh (1991), 1	23°45′N	360	26.5	1,040	7.0	1.1	400	3.3
Izquierdo et al. (2003), 2	23°02′N	30	24.6	1,300	5.9	3.1	550	2.3
Sahani and Behera (2001), 1	22°00′N	170	25.0	1,670	ND	1.4	150	2.7
Behera and Sahani (2003), 1	22°00′N	170	25.0	1,960	6.3	2.4	250	1.7
Prasad et al. (1995), 1	21°22′N	150	25.0	1,400	6.6	1.5	420	2.8
Basu and Behera (1993), 1	19°59′N	260	24.0	1,500	6.6	3.6	400	1.1
Zhang and Zhang (2003), 1	19°31′N	150	23.3	1,830	5.1	ND	120	1.4
Galicia and García-Oliva (2004), 6	19°30′N	100	24.6	750	7.0	2.0	340[c,d]	1.1
Galicia and García-Oliva (2008), 3	19°30′N	100	24.6	750	7.2	2.2	490	1.6
Toledo-Aceves and Garcia-Oliva (2008), 4	19°29′N	240	24.6	750	7.0	8.0	1,960[a,b]	3.0
Zhang et al. (2007), 1	19°28′N	150	23.3	1,830	4.5	0.7	220	2.0
Geissen and Morales Guzman (2006), 1	17°29′N	600	25.4	3,900	5.6[e]	3.0	170	0.5
Sierra and Marbán (2000), 2	16°15′N	40	25.5	4,000	5.5	1.9	190[c]	1.1
Sall et al. (2006), 1	13°45′N	10	26.2	650	6.1	1.0	120	0.8
Bilgo et al. (2007), 8	11°51′N	330	29.0	850	6.6[e]	0.4	70	1.2
Groffman et al. (2001), 2	10°30′N	90	27.5	1,600	5.4	3.9	1,140[d]	2.5
Tornquist et al. (1999), 1	10°26′N	40	26.5	3,910	5.1	4.2	490[a,b]	1.3
Henrot and Robertson (1994), 2	9°50′N	670	26.0	4,300	5.5	2.1	950	2.9
Cleveland et al. (2003), 2	8°43′N	160	26.0	5,100	5.5	4.5	780	1.5
Michelsen et al. (2004), 3	8°06′N	580	28.0	1,100	6.8	ND	520	1.3
Andersson et al. (2004), 1	8°01′N	550	28.5	900	7.0[e]	1.0	1,360	3.4
Ayanaba et al. (1976), 3	7°23′N	210	26.5	1,120	6.7	1.1	330	2.8

(*continued*)

Table 2.3 (continued)

Reference, number of sites	Latitude	ASL (m)	Temperature (°C)	Rainfall (mm)	pH (H_2O)	Total N (mg g^{-1} soil)	Microbial biomass C (μg g^{-1} soil)	Microbial biomass C/soil organic C (%)
Agele et al. (2005), 1	7°05′N	270	26.2	1,250	7.3	3.4	560[a]	1.1
Oberson et al. (2001), 2	4°30′N	150	27.0	2,240	4.9	1.7	350[a,b,f]	1.3
Gijsman et al. (1997), 1	4°00′N	200	27.0	2,200	4.4	1.2	440[a,b]	1.7
Luizao et al. (1992), 1	3°08′S	30	24.6	2,100	3.7	ND	990	4.0
Cerri et al. (2003), 1	10°10′S	140	25.6	2,200	6.2	1.2	260[a]	1.5
Cerri et al. (2006), 5	10°10′S	140	25.6	2,200	5.9	1.2	560[a]	3.9
Cantarutti et al. (2002), 1	16°40′S	110	24.0	1,300	5.5	0.8	130[a,b]	1.4
de Oliveira et al. (2004), 4	17°13′S	660	25.7	1,750	5.1	1.2	150[a,b]	0.8
Waldrop et al. (2000), 1	17°30′S	270	26.0	1,730	4.6	4.0	860	1.1
Rabary et al. (2008), 4	19°46′S	1600	16.9	1,450	5.7	5.0	390	0.6
Northup et al. (1999), 5	20°11′S	220	24.7	530	6.7	0.5	220	2.5

Sequentially shown are: reference, number of sites analyzed, site parameters (latitude, elevation ASL, mean annual temperature, mean annual rainfall), soil pH, soil total N, soil microbial biomass C, soil microbial biomass C/soil organic C ratio; *ND* not determined

[a]corrected k_{EC} value

[b]corrected k_{EN} value

[c]corrected k_C value

[d]corrected k_N value

[e]adjusted soil pH

[f]corrected k_{EP} value

Table 2.4 Forest soils of the tropics: basic parameters and carbon-related microbial properties

Reference, number of sites	Latitude	ASL (m)	Temperature (°C)	Rainfall (mm)	pH (H_2O)	Total N (mg g^{-1} soil)	Microbial biomass C (μg g^{-1} soil)	Microbial biomass C/soil organic C (%)
Islam and Weil (2000), 2	24°00′N	20	26.0	1,800	5.0	1.1	300	2.9
Srivastava and Singh (1991), 1	23°45′N	360	26.5	1,040	6.4	2.2	610	2.8
Sahani and Behera (2001), 1	22°00′N	170	25.0	1,670	ND	2.6	900	3.8
Behera and Sahani (2003), 2	22°00′N	170	25.0	1,960	6.3	2.2	740	3.5
Xu et al. (2007), 1	21°56′N	720	22.0	1,400	4.2	1.4	380	2.4
Mao et al. (1992), 7	21°28′N	40	23.0	1,600	4.6	0.3	120	1.4
Prasad et al. (1995), 1	21°22′N	150	25.0	1,400	6.9	2.0	640	3.2
Basu and Behera (1993), 1	19°59′N	260	24.0	1,500	6.7	6.7	820	1.3
Montano et al. (2007), 2	19°29′N	240	24.6	750	6.5	2.2	530	1.8
Toledo-Aceves and Garcia-Oliva (2008), 1	19°29′N	240	24.6	750	7.4	4.0	1,250[a,b]	3.0
Templer et al. (2005), 1	19°0′N	50	25.2	2,000	6.0	ND	2,830[a,b]	1.9
Saynes et al. (2005), 4	18°28′N	1070	24.5	850	7.1	2.1	570[c]	1.4
Li et al. (2006a), 2	18°18′N	400	22.1	3,500	4.9	ND	400	0.8
Salamanca et al. (2002, 2006), 8	16°06′N	30	28.0	2,300	6.5	1.3	380	2.9
Duponnois et al. (2005), 1	14°10′N	10	25.0	700	5.2	3.9	80	0.2
Motavalli et al. (2000), 1	13°31′N	110	27.3	2,160	7.3	ND	1,400[d]	2.7
Dinesh et al. (2006), 16	12°10′N	1	30.1	3,100	5.5	1.4	410	2.6
Dinesh et al. (2003), 4	11°37′N	40	30.1	3,100	5.2	1.9	600	2.5
Dinesh et al. (2004b), 3	11°37′N	40	30.1	3,100	5.9[e]	1.7	390	2.9
Groffman et al. (2001), 4	10°30′N	90	27.5	1,600	5.8	3.3	1,060	3.9
Vance and Nadkarni (1990), 1	10°18′N	1550	20.0	2,000	4.7	9.8	1,950	1.3
Mazzarino et al. (1993), 1	9°53′N	600	22.0	2,640	5.0	2.8	160[c,d]	0.4
Henrot and Robertson (1994), 2	9°50′N	670	26.0	4,300	5.7	2.4	1,590	4.3
Cleveland et al. (2003), 2	8°43′N	160	26.0	5,100	5.7	6.0	1,300	2.0
Jensen et al. (2001), 1	8°09′N	550	28.5	950	6.2	0.8	230[c]	1.4
Michelsen et al. (2004), 2	8°09′N	580	28.5	900	6.8	ND	270	1.1
Wick et al. (1998), 1	7°30′N	210	26.2	1,250	6.7	0.9	360	3.2
Ayanaba et al. (1976), 5	7°23′N	210	26.5	1,120	6.4	0.9	220	2.0

(*continued*)

Table 2.4 (continued)

Reference, number of sites	Latitude	ASL (m)	Temperature (°C)	Rainfall (mm)	pH (H_2O)	Total N (mg g^{-1} soil)	Microbial biomass C (μg g^{-1} soil)	Microbial biomass C/soil organic C (%)
Tian (1998), 1	7°23′N	210	26.5	1,300	6.4	ND	550	3.5
Priess and Fölster (2001), 3	5°00′N	1180	20.6	2,200	4.9[e]	6.9	1,260	1.1
Adachi et al. (2006), 4	2°50′N	20	27.5	1,900	4.0[e]	1.4	60	0.3
Bossio et al. (2005), 2	0°02′N	1540	18.5	1,800	4.6	ND	380	0.8
Luizao et al. (1992), 1	3°08′S	30	24.6	2,100	3.7	ND	940	3.1
Turgay et al. (2002), 4	5°08′S	650	24.0	1,750	5.3	3.2	950	2.6
Cerri et al. (2003), 1	10°10′S	140	25.6	2,200	4.9	1.1	200[d]	1.7
Cantarutti et al. (2002), 1	16°40′S	110	24.0	1,300	5.5	0.8	180[c,d]	2.0
de Oliveira et al. (2004), 1	17°13′S	660	25.7	1,750	5.0	1.0	150[c,d]	1.0
Nogueira et al. (2006), 5	23°27′S	580	20.9	1,620	6.0[e]	ND	810[d]	2.9

Sequentially shown are: reference, number of sites analyzed, site parameters (latitude, elevation ASL, mean annual temperature, mean annual rainfall), soil pH, soil total N, soil microbial biomass C, soil microbial biomass C/soil organic C ratio; *ND* not determined

[a]corrected k_C value

[b]corrected k_N value

[c]corrected k_{EN} value

[d]corrected k_{EC} value

[e]adjusted soil pH

2.2.2 Soil Chemical Properties

The soil pH was usually measured in water suspension. If the pH was measured in 0.01 M $CaCl_2$ or 1 M KCl solution, the data were converted to pH in water by multiplication by 1.1, this ratio having been obtained from those references where two pH values were presented (Mao et al. 1992; Joergensen and Castillo 2001; Cerri et al. 2006). The majority of soil organic C values were obtained by the Walkley-Black method (Srivastava and Singh 1991; Mazzarino et al. 1993; Motavalli et al. 2000), using potassium dichromate sulphuric acid oxidation as described, for example, by Nelson and Sommers (1982). Loss of ignition was sometimes used to determine soil organic C (Northup et al. 1999; Michelsen et al. 2004). Total N was measured in the majority of cases by the Kjeldahl procedure (Srivastava and Singh 1991; Northup et al. 1999; Motavalli et al. 2000). On the other hand, gas chromatographic determination of total C and total N were often used by different authors (Joergensen and Castillo 2001; Ndiaye et al. 2004; Li et al. 2006a, b). A variety of other methods were also applied for determining organic C and total N in soil.

2.2.3 Microbial Biomass Indices

Microbial biomass C was obtained by fumigation extraction (FE) (Vance et al. 1987) at 280 sites or 75.3% of the data, by fumigation incubation (FI) (Jenkinson and Powlson 1976) at 67 sites or 18.0% of the data, by substrate-induced respiration (Anderson and Domsch 1978; Kaiser et al. 1992; Lulu and Insam 2000a, b) at 18 sites or 4.9% of the data, by ATP (Jenkinson and Oades 1979; Adachi et al. 2006) at five sites or 1.3% of the data, and by direct microscopy (Babiuk and Paul 1970; Lodge and Ingham 1991; Li et al. 2006a) at two sites or 0.5% of the data. The microbial biomass C values obtained by FE were corrected if the conversion value of 0.38 for dichromate oxidation (Vance et al. 1987) or 0.45 for ultraviolet or oven oxidation (Wu et al. 1990; Joergensen 1996a) had not been used. At 45 sites, the microbial biomass C data were obtained by measuring ninhydrin-reactive N according to Amato and Ladd (1988) or Joergensen and Brookes (1990). The microbial biomass C values obtained by FI were corrected if the conversion value of 0.45 (Jenkinson and Powlson 1976; Joergensen 1996a) had not been used. Data were not used if the FI method was obviously incorrectly applied (Salinas-García et al. 2002).

The soil microbial biomass is not completely extractable (FE method) or decomposable after fumigation (FI method). For this reason, conversion values must be used to account for the nonextractable (FE method) or the nondecomposable (FI method) fraction (Jenkinson 1988). The conversion of measured data into microbial biomass values is an important step for assessing the flux of energy and elements (Jenkinson and Ladd 1981). Biomass values serve as an internal control by

relating microbial growth and CO_2 evolution data, and they help to prove the soundness of the values in comparison with other data. As the calibration of conversion values is difficult and erroneous, the use of a single standard conversion value for each element is recommended also for tropical soils (Joergensen 1996a; Joergensen and Mueller 1996). In particular, the calibration of the FE method was not affected by soil pH and clay content (Kaiser et al. 1992). Only the conversion of ninhydrin-reactive N to microbial biomass C leads to underestimation below pH 4.8 according to Joergensen (1996b), using the constant factors of Amato and Ladd (1988) and Joergensen and Brookes (1990).

ATP was converted to microbial biomass C on the basis of the ATP to microbial biomass C ratio of 10.5 μmol g^{-1} obtained by Contin et al. (2001). Direct microscopic counts were converted to microbial biomass C assuming an average C content of 47% (Jenkinson and Ladd 1981).

Microbial biomass N was obtained by FE (Vance et al. 1987) at 141 sites or 89.8% of the data and by FI (Jenkinson and Powlson 1976) at 16 sites or 10.2% of the data. The microbial biomass N values obtained by FE were corrected if the conversion value of 0.54 had not been used (Brookes et al. 1985; Joergensen and Mueller 1996). The microbial biomass N values obtained by FI were corrected if the conversion value of 0.68 (Jenkinson and Powlson 1976) had not been used. Microbial biomass P can only be measured by FE (Brookes et al. 1982). The microbial biomass P values were corrected if the conversion value of 0.40 had not been used (Brookes et al. 1982).

2.2.4 Basal Respiration

Basal respiration was usually measured in a closed glass vessel for between 10 h and 10 days at between 20 and 30°C. In some cases, the data were unit-corrected if they were suspiciously high or low. All data were adjusted, if necessary, to a 25°C rate per day using the rate-modifying factor (f) for temperature (= T in °C) effects of the Rothamsted Carbon model (Jenkinson et al. 1987): $f = 47.9/(1 + e^{(106/(T + 18.3)})$.

2.2.5 Statistical Evaluation

The results presented in Tables 2.1–2.4 are arithmetic means and expressed on an oven-dry basis. Those in Tables 2.5 and 2.6 are arithmetic or geometric means. The significance of land-use or soil-type-specific effects was tested by one-way analysis of variance using the PLSD-test (Fisher's protected least significant difference). Relationships between selected soil biological and chemical properties were analyzed by regression analysis. Data were ln-transformed if they did not fit a normal distribution. All statistical analyses were performed using StatView 5.0 (SAS Institute Inc.).

Table 2.5 General and land use-specific means of site characteristics and chemical properties in soils of the tropics covered in the references used in this review

Characteristic	Type of soil				
	General	Arable	Plantation	Pasture	Forest
Latitude	13°20′ (372)	13°28′ *ab* (152)	11°17′ *b* (42)	13°50′ *a* (73)	13°39′ *ab* (105)
Mean annual temperature (°C)	25.4 (372)	24.4 *b* (152)	27.0 *a* (42)	25.9 *a* (73)	26.0 *a* (105)
Mean annual precipitation (mm)	1,800 (372)	1,510 *c* (152)	2,420 *a* (42)	1,660 *c* (73)	2,070 *b* (105)
Sampling depth (mm)	160 (371)	180 *b* (152)	230 *a* (42)	110 *c* (73)	130 *c* (104)
Clay (%)	30 (263)	35 *a* (127)	30 *ab* (31)	21 *c* (45)	26 *bc* (61)
pH (H_2O)	5.9 (369)	6.1 *a* (151)	5.0 *c* (42)	6.1 *a* (72)	5.7 *b* (104)
Soil organic C (mg g^{-1} soil)[a]	16.3 (372)	12.5 *c* (152)	14.9 *bc* (42)	17.7 *b* (73)	23.2 *a* (105)
Total N (mg g^{-1} soil)[a]	1.3 (305)	1.0 *c* (112)	1.3 *b*c (35)	1.3 *b* (68)	1.7 *a* (90)
Total P (mg g^{-1} soil)[a]	0.31 (89)	0.48 *a* (41)	0.32 *ab* (2)	0.20 *b* (32)	0.22 *b* (14)
Soil organic C/total N[a]	12.3 (305)	11.9 *bc* (112)	11.1 *c* (35)	13.4 *a* (68)	12.5 *ab* (90)

For each combination of characteristic and soil type, the number of observations is shown in parentheses; figures within a row followed by different letters in italics are significantly different according to the PLSD-test
[a]geometric mean

Table 2.6 General and land use-specific means of biological properties in soils of the tropics covered in the references used in this review

Characteristic	Type of soil				
	General	Arable	Plantation	Pasture	Forest
Microbial biomass C (μg g^{-1} soil)[a]	270 (372)	190 *c* (152)	280 *b* (42)	280 *b* (73)	450 *a* (105)
Microbial biomass N (μg g^{-1} soil)[a]	39 (157)	24 *b* (46)	32 *b* (24)	49 *a* (26)	56 *a* (61)
Microbial biomass P (μg g^{-1} soil)[a]	3.9 (46)	2.9 *b* (37)	ND	14.3 *a* (5)	14.8 *a* (4)
Basal respiration (CO_2-C g^{-1} soil d^{-1})[a]	13 (192)	11 *b* (89)	10 *b* (22)	12 *b* (19)	20 *a* (62)
Ergosterol (μg g^{-1} soil)[a]	0.60 (61)	0.29 *c* (26)	0.42 *b* (16)	ND	1.39 *a* (19)
ATP (nmol g^{-1} soil)[a]	1.6 (53)	ND	1.0 *b* (18)	ND	2.1 *a* (35)
Microbial biomass C/N	10.5 (157)	12.0 *a* (46)	11.0 *ab* (24)	7.5 *c* (26)	10.4 *b* (61)
Microbial biomass C/P[a]	49 (46)	52 *a* (37)	ND	27 *a* (5)	61 *a* (4)
Ergosterol/microbial biomass C (%)[a]	0.27 (61)	0.28 *a* (26)	0.27 *a* (16)	ND	0.27 *a* (19)
ATP/microbial biomass C (μmol g^{-1})	5.3 (48)	ND	4.3 *b* (17)	ND	5.8 *a* (31)
Microbial biomass C/soil organic C (%)[a]	1.7 (374)	1.5 *b* (152)	1.9 *a* (42)	1.6 *ab* (73)	1.9 *a* (105)
qCO_2 (mg CO_2-C g^{-1} biomass C d^{-1})[a]	52 (192)	59 *a* (89)	35 *b* (22)	61 *a* (19)	48 *ab* (62)

For each combination of characteristic and soil type, number of observations is shown in parentheses; figures within a row followed by different letters in italics are significantly different according to the PLSD-test; *ND* not determined
[a]geometric mean

2.3 Environmental Variables

Data were obtained from 26 countries in tropical regions. About 38% of the data were obtained from Asia (11% of the total number from the Andaman Islands and 10% from India), 34% from Latin America (11% from Brazil and 7% from Nicaragua), 24% from Africa (8% from Nigeria and 5% from Ethiopia), and 3% from other tropical regions such as Australia, Guam and Tahiti. However, no information is available on soil micro-organisms for many tropical countries in refereed international journals.

The mean latitude of all sampling sites was 13°20′, which is close to the midpoint between the equator and the 24°00′ latitude, which were set as northern and southern boundaries (Table 2.5). The soils of most land-use forms are evenly distributed over the tropics, except the plantation soils, which were on average closest to the equator and had the highest mean annual temperature of 27.0°C and the highest mean annual precipitation of 2,420 mm. The plantation soils also had the lowest mean soil pH of 5.0. In general, the tropical soils were moderately acidic, with a mean soil pH of 5.9. They had a considerable clay content of 30%, which was highest in the group of arable soils. The lowest soil pH of around 5.0 was observed in Oxisols and Inceptisols, the highest soil pH of around 6.6 in Vertisols and Alfisols. Soil types were assigned for 290 sites or 78% of the total number, which decreased in percent of the total number from Oxisols (22%) > Entisols (18%) > Ultisols (11%) > Vertisols (9%) > Andisols (8%) > Alfisols (5%) > Inceptisols (4%) > Mollisols (1%).

The mean contents of soil organic C and total N were 16.3 and 1.3 mg g^{-1} soil respectively (Table 2.5). These contents declined in the order forest > pasture > plantation > arable soils. The soil C/N ratio varied in most soils between 12 and 14 and was lowest at 11.1 in the plantation soils. It is obvious that tropical forest soils contain considerable amounts of organic matter in the A-horizon of the mineral soil. Decomposition processes not only occur in the litter layer, which was only analyzed by a minority of references (Vance and Nadkarni 1990; Priess and Fölster 2001; Li et al. 2006a, b), but also in the A horizon of the mineral soil. Soil organic matter decreased apparently with increasing intensity of human land use and decreasing C input by the vegetation. However, only a minority of references presented data on the annual production of aboveground plant biomass (Duponnois et al. 2005; Li et al. 2006a, b), which was usually related to the C input by roots (Marschner et al. 2002; Galicia and García-Oliva 2008). The belowground plant biomass is an important source of organic matter in most tropical soils (Sierra and Nygren 2005; Kaonga and Coleman 2008), as harvest residues are often used as energy sources or removed by burning (Castillo and Joergensen 2001; Bationo et al. 2007). The use of crop residue mulch and compost as C and nutrient source for arable soils is still rare (Izquierdo et al. 2003; Bhattacharyya et al. 2005).

Information on total P is rare and only available for 24% of the soils. This is surprising, as total P is very low in many tropical soils, especially in Oxisols (Gijsman et al. 1997; Northup et al. 1999; Andersson et al. 2004; Bilgo et al. 2007; Zhang et al. 2007). P deficiency not only limits plant growth in tropical soils, it also has strong negative effects on microbial growth (Duah-Yentumi et al. 1998; Salamanca et al. 2006; Gnankambary et al. 2008).

2.4 Soil Microbial Biomass

The mean content of all microbial biomass C data was 270 μg g^{-1} soil (Table 2.7), ranging from 20 to 2,830 μg g^{-1} soil (Fig. 2.1a). Microbial biomass C was significantly highest in the forest soils, on a medium level in pasture and plantation soils

Table 2.7 Correlation coefficients between soil organic matter content, soil total N content and soil microbial properties in soils of the tropics covered in the references used in this review

	Total N	Microbial biomass C	Microbial biomass N	Basal respiration	Ergosterol	ATP
Soil organic C	0.92 (305)	0.66 (372)	0.78 (157)	0.58 (192)		0.52 (53)
Total N		0.68 (305)	0.85 (148)	0.63 (159)		0.62 (53)
Microbial biomass C			0.85 (157)	0.67 (192)	0.73 (61)	0.88 (48)
Microbial biomass N				0.60 (77)		0.85 (48)
Basal respiration					0.72 (52)	0.89 (48)
Ergosterol						0.82 (48)

For each combination of characteristics analyzed, the number of observations is indicated in parentheses. All correlation coefficients are significant at $P < 0.0001$

and significantly lowest in the arable soils, reaching only 40% of the forest soils (Table 2.7). The mean content of all microbial biomass N data was 39 μg g^{-1} soil, ranging from 7 to 353 μg g^{-1} soil (Fig. 2.1b). However, the differences between the four groups of land-use systems were less significant, as the amount of data was 60% lower (Table 2.7). The mean of all microbial biomass C/N ratios was 10.5; it was about 7.5 in the pasture soils and was, consequently, significantly lower for pasture that for the other three groups of land-use management, where the mean C/N ratio was 11.1. Microbial biomass C and microbial biomass N were closely interrelated and also showed significant correlations with soil organic C and total N (Table 2.7). However, microbial biomass N showed closer correlations to soil organic C and total N than microbial biomass C. Microbial biomass P followed microbial biomass C with an average C/P ratio of 49 (Table 2.7). The differences between the land-use systems were not significant.

The total geometric mean for microbial biomass C in tropical soils is only 20% below the worldwide average of 330 μg g^{-1} soil reported by Wardle (1998). This is amazing, considering that the decomposition of plant residues and the turnover of soil organic matter is much higher under tropical conditions (Jenkinson and Ayanaba 1977; Cerri et al. 2003; Diels et al. 2004). This means that the C input by plants must be much higher in tropical ecosystems or that the turnover is only increased for a short time after fresh organic residues have entered the soil. However, low pH values may counteract positive temperature effects on the microbial turnover of organic matter (Wardle 1998). The relative difference between arable and forest soils was markedly stronger for microbial biomass C than for soil organic C. This indicates that the microbial biomass content reacts much more strongly on the C input by plants than does the soil organic content, as suggested by Powlson et al. (1987). Another reason might be that tillage leads to a dilution of microbial biomass on a larger soil volume with a higher bulk density, which is accentuated by a larger sampling depth of the arable soils in comparison to that of the forest soils. Water and wind erosion, especially when the soils are bare or the crops are small and developing, may additionally lead to losses of organic matter in the surface horizon

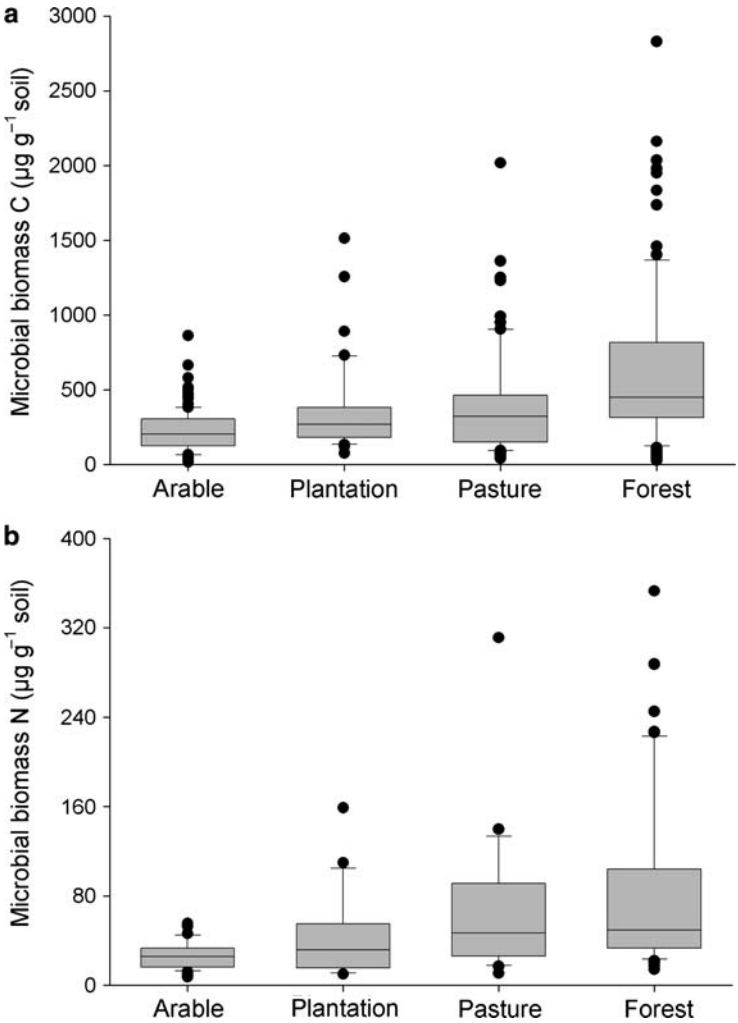

Fig. 2.1 Land use-specific box plots for the content of (**a**) microbial biomass C and (**b**) microbial biomass N in soils of the tropics. For each type of soil, the box plots show the smallest observation, the lower quartile, the median, the upper quartile, and the largest observation, with observations considered as outliers being indicated as *dots*

(Bationo et al. 2007). Irrigation of arable sites may increase the turnover of microbial biomass and soil organic matter during dry periods, but the reverse is also possible, depending on the interaction of water and oxygen supply (Yavitt et al. 1993; Witt et al. 2000; Ndour et al. 2008). Wildfires and prescribed burning reduce the aboveground biomass, but may have positive effects on the belowground C inputs, as suggested by the observed increases of the soil microbial biomass in surface horizons (Jensen et al. 2001; Andersson et al. 2004; Michelsen et al. 2004).

Fires may also increase the soil organic C content, due the incorporation of charcoaled organic residues (Glaser et al. 2002).

The reasons for the relatively large microbial biomass C/N ratios exceeding 10 in tropical soils compared to arable soils from a humid climate are not fully understood (Joergensen and Emmerling 2006). A sometimes stated explanation is the possibility of fungal dominance in soils with a large microbial biomass C/N ratio (Dilly et al. 2003; Moore et al. 2005). However, as explained below, a shift towards fungi is not likely to be the only explanation for the observed wide microbial biomass C/N ratios. In some cases, P limitation has been demonstrated as a possible explanation (Salamanca et al. 2006). However, limitation of other nutrients such as S and Zn might also be responsible for the large C/N ratio of the microbial biomass in tropical soils. Changes in the microbial biomass C/N ratio may also indicate segregation of the microbial community according to their enzymatic and catabolic potential, along with organic matter quality and energy flux, as discussed below (Lulu and Insam 2000a)

The mean microbial biomass C/P ratio of the tropical soils was more than four times the mean of 11 measured in 44 German agricultural soils (Jörgensen 1995) and roughly twice the mean value of around 25 found in sub-tropical India (Singh et al. 1991; Srivastava and Lal 1994). The microbial biomass C/P ratio shows considerably more variation than the microbial biomass C/N ratio (Anderson and Domsch 1980), contrasting the view of Cleveland and Liptzin (2007) that rather uniform microbial biomass C/P ratios exist in soil. Its variability is caused by the possibility for bacteria, and also for fungi, to store excess P in the form of cell-internal polyphosphates and cell wall components, e.g., teichoic acids (Grant 1979; Nielsen et al. 2002; Oberson and Joner 2005). These storage components can be used as a phosphate source in times of P limitation (Oberson and Joner 2005). The application of inorganic P and organic P components to soil significantly decreased the microbial biomass C/P ratio and strongly reflects P availability to soil micro-organisms (Oehl et al. 2004; Muhammad et al. 2007). The microbial biomass C/P ratio is increased by low P availability, but also by low N availability in combination with high C availability (Anderson and Domsch 1980). However, it is possible that microbial biomass P has been underestimated due to methodological problems, e.g., with alkaline extractants in acidic soils, especially in the presence of aluminum and iron oxides (Wu et al. 2000).

2.5 Basal Respiration Rate

The mean basal respiration was 13 μg CO_2 g^{-1} soil d^{-1} and increased in the order plantation < arable < pasture < forest soils. However, only the differences between forest and arable soils and forest and plantation soils were significant, due to the large variation within the four soil groups. Basal respiration is highly affected by the incubation conditions, e.g., temperature and the sample pretreatment, especially sieving (Joergensen 1996a). The mean basal respiration rate for

tropical soils was only slightly above the mean basal respiration rate of 11 μg CO_2-C g^{-1} soil measured in 62 German soils (Jörgensen 1995). This indicates that most data obtained from the references listed in Tables 2.1–2.4 were accurate and suggests that similar levels of mineralizable soil organic matter exist in tropical soils and soils from a temperate humid climate.

2.6 Microbial Biomass C-to-Soil Organic C Ratio and qCO_2

The mean microbial biomass C-to-soil organic C ratio was 1.7% in all soils (Table 2.7), ranging from 0.1 to 8.2% (Fig. 2.2a). It was lowest in the arable soils and highest in the plantation and forest soils (Table 2.7). The microbial biomass C-to-soil organic C ratio is an important index for organic matter availability to the soil microbial community (Anderson and Domsch 1989). This suggests a better availability of organic matter in soils with permanent tree vegetation than in arable and grassland soils. However, the microbial biomass C-to-soil organic C ratios are generally lower in tropical soils than in soils from a humid temperate climate, which was 2.6% in 26 arable soils (Anderson and Domsch 1989) or 2.2% in 27 arable and 2.3% in 17 grassland soils (Jörgensen 1995). The microbial biomass C-to-soil organic C was exceptionally low in Andisols, with a mean of 0.6%, due to aluminium oxides fixing organic matter by covalent bondings, which make this organic matter unavailable to soil micro-organisms (Zunino et al. 1982). An even more important reason is most likely the generally low pH level of most soils (Anderson and Domsch 1993; Anderson and Joergensen 1997). Highest microbial biomass C-to-soil organic C ratios were measured in Vertisols, with a mean of 2.2% and in Inceptisols with a mean of 2.5%. The microbial biomass C-to-soil organic C ratio in the present tropical soils was negatively correlated with the soil organic C-to-total N ratio, which is in accordance with Jörgensen (1995), and positively correlated with the microbial biomass C/N ratio (Table 2.8). This indicates that the soil organic matter quality had a strong effect on the substrate availability to soil micro-organisms, on the microbial biomass C/N ratio, and probably also on the microbial biomass C/P ratio (see above).

The mean metabolic quotient was 52 mg CO_2-C g^{-1} microbial biomass C d^{-1} (Table 2.7), ranging from 8 to 520 (Fig. 2.2b). The land-use specific qCO_2 values increased in the order plantation $<$ forest $<$ arable soils $<$ pasture soils (Table 2.7, Fig. 2.2b). Only the differences between arable soils and plantation soils and between pasture soils and plantation soils were significant (Table 2.7). The ratio of basal respiration to microbial biomass, the metabolic quotient qCO_2, is an important index for the age structure of the microbial biomass, i.e., the higher the qCO_2, the younger the mean age of the microbial population (Anderson and Domsch 1990; Dilly 2005). The significant inverse relationship of qCO_2 with the microbial biomass C-to-soil organic C ratio (Table 2.8) reveals the interdependence of catabolism and anabolism (Anderson and Domsch 1990). Mean qCO_2 value of the tropical soils was more than twice as high as the mean qCO_2 value of 21 in 99

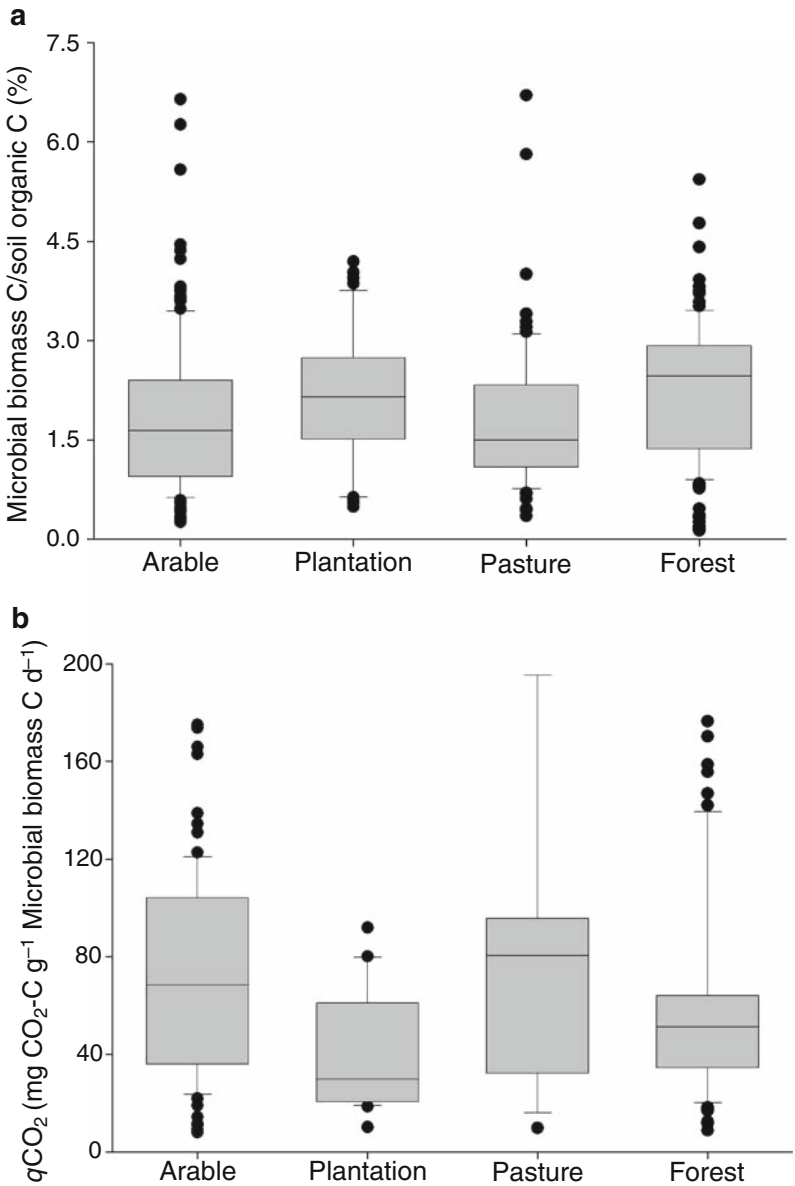

Fig. 2.2 Land use-specific box plots for (**a**) the microbial biomass C/soil organic C ratio and (**b**) the metabolic quotient qCO_2 in soils of the tropics. For each type of soil, the box plots show the smallest observation, the lower quartile, the median, the upper quartile, and the largest observation, with observations considered as outliers being indicated as *dots*

Table 2.8 Correlation coefficients between ratios of values for properties related to soil organic matter content and soil microbial biomass, in soils of the tropics covered in the references used in this review

	Microbial biomass C/soil organic C	qCO_2	ATP/microbial biomass C
Soil organic C/total N	−0.31 (305)****		
Microbial biomass C/N	0.49 (157)****		
Microbial biomass C/soil organic C		−0.33 (192)****	
qCO_2			0.52 (48)***
Ergosterol/microbial biomass C			0.57 (27)**

For each combination of ratios analyzed, the number of observations is indicated in parentheses
**$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$

German soils under different land-use forms (Anderson and Domsch 1990; Jörgensen 1995). The generally lower pH (Anderson and Domsch 1993), and most probably also the presence of iron and aluminium oxides in Andisols (Joergensen and Castillo 2001), seem to increase the metabolic quotient considerably. Sub-lethal stress lowers the efficiency of substrate use, i.e., more substrate must be catabolized to CO_2 and less substrate can be incorporated into the microbial biomass (Anderson and Domsch 1993; Anderson and Joergensen 1997). This relationship seems to hold for soils all over the world.

2.7 ATP and Ergosterol

ATP and ergosterol contents were only measured in a minority of soils (Table 2.7). ATP was mainly determined in the Philippines (Salamanca et al. 2002, 2006) and the Andaman Islands (Dinesh et al. 2003, 2004a, b, 2006; Dinesh 2004), ergosterol in Nicaragua (Joergensen and Castillo 2001) and again in the Andaman Islands (Dinesh et al. 2003, 2004a; Dinesh 2004). The ATP content of the forest soils markedly exceeded that of the plantation soils (Table 2.7), leading to a significantly larger ATP/microbial biomass C ratio. The ATP concentration in the microbial biomass of all tropical soils was in the lower part of the range presented by Dyckmans et al. (2003). However, a negative relationship between the ATP/microbial biomass C ratio and the microbial biomass C/N ratio repeatedly observed by Salamanca et al. (2002, 2006) could not be confirmed in the present set of soils. In contrast, positive linear relationships were observed between qCO_2 and the ergosterol/microbial biomass C ratio as observed by Chander et al. (2001) and Salamanca et al. (2006), but not with the microbial biomass C/N ratio. This suggests a negative relationship between substrate use efficiency and presence of saprotrophic fungi. The present results are in line with Scheller and Joergensen (2008), but contradict the view that fungi are more efficient in the use of organic substrates (Sakamoto and Oba 1994; Jastrow et al. 2007).

ATP was significantly correlated to all soil organic matter and microbial biomass indices analyzed (Table 2.7). In contrast, ergosterol was only correlated with ATP, microbial biomass C, and basal respiration. The ergosterol content always increased significantly in the order arable < plantation < forest soils. The mean ergosterol/microbial biomass C ratio was 0.28%, without significant effects of the land-use system. However, the mean ergosterol/microbial biomass C ratio, which is an indicator for living saprotrophic fungi (Joergensen and Wichern 2008), was only half that of soils from a temperate humid climate (Djajakirana et al. 1996). If ergosterol is recalculated into fungal biomass C by multiplication by 90 (Djajakirana et al. 1996), fungi represent only 25% of total microbial biomass C in tropical soils. In contrast, the few data on the ratio of fungal to bacterial biomass indicate that fungi dominate the microbial biomass in tropical soils by roughly 60% (Prasad et al. 1995; Sahani and Behera 2001) or by 87% (Li et al. 2006a, b), and do not fall below 50% (Henrot and Robertson 1994).

This is in line with data on the ratio of fungal residue C to bacterial residue C, calculated on the basis of fungal glucosamine and bacterial muramic acid, which suggest that microbial residue C in soils from semi-arid West Africa consists of 77% fungal residues. This is close to the worldwide average of 75% for all forms of land-use management (Joergensen and Wichern 2008). The present data suggest that the fungi of tropical soils generally have very low ergosterol contents, perhaps indicating a large contribution of arbuscular mycorrhizal fungi, which do not contain ergosterol (Olsson et al. 2003), to the total fungal biomass of soils (Rillig et al. 2001).

2.8 Conclusions

For soils of the tropics, the relationships between microbial biomass C, basal respiration, and soil organic matter are generally similar to those of soils from a temperate humid climate. This is amazing, considering the large variety of soil types and the fact that all these soil biological and chemical properties were measured using a wide variety of methods. This gives confidence that microbial biomass C, basal respiration, and soil organic C are useful indices for soil fertility in tropical soils. Those soils are characterized by low pH, low microbial biomass C-to-soil organic C ratios and high metabolic quotients qCO_2. This is especially true for arable soils, indicating the negative impact of intensive land use on soil fertility. Compost addition, mulching, alley cropping, and reduced tillage are recommended to improve soil biological quality indices at arable sites. Increased efforts should be made to monitor the spatial heterogeneity of soil biological indices, and sampling should be carried out down to a 20- or 30-cm depth in 10-cm steps. The calculation of C budgets requires information on bulk density, and on the amount of organic C stored in the litter layer as well as in the aboveground plant biomass. Despite the importance of phosphorus in tropical soils, the relationship of microbial biomass P to the contents of total P and soil organic matter is a severely neglected area of soil

biological research. Likewise, little information is available on the respective contribution of fungi and bacteria to the microbial biomass or to the microbial residue fraction of tropical soils.

References

Adachi M, Bekku YS, Rashidah W, Okuda T, Koizumi H (2006) Differences in soil respiration between different tropical ecosystems. Appl Soil Ecol 34:258–265

Adeboye MKA, Iwuafor ENO, Agbenin JO (2006) The effects of crop rotation and nitrogen fertilization on soil chemical and microbial properties in a Guinea Savanna Alfisol of Nigeria. Plant Soil 281:97–107

Agele SO, Ewulo BS, Oyewusi IK (2005) Effects of some soil management systems on soil physical properties, microbial biomass and nutrient distribution under rainfed maize production in a humid rainforest Alfisol. Nutr Cycl Agroecosyst 72:121–134

Amato M, Ladd JN (1988) Assay for microbial biomass based on ninhydrin-reactive nitrogen in extracts of fumigated soil. Soil Biol Biochem 20:107–114

Anderson JPE, Domsch KH (1978) A physiological method for quantitative measurement of microbial biomass in soils. Soil Biol Biochem 10:519–525

Anderson JPE, Domsch KH (1980) Quantities of plant nutrients in the microbial biomass of selected soils. Soil Sci 130:211–216

Anderson TH, Domsch KH (1989) Ratios of microbial biomass C to total organic carbon in arable soils. Soil Biol Biochem 21:471–479

Anderson TH, Domsch KH (1990) Application of eco-physiological quotients (qCO_2 and qD) on microbial biomasses from soils of different cropping histories. Soil Biol Biochem 22:251–255

Anderson TH, Domsch KH (1993) The metabolic quotient for CO_2 (qCO_2) as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils. Soil Biol Biochem 25:393–395

Anderson TH, Joergensen RG (1997) Relationship between SIR and FE estimates of microbial biomass C in deciduous forest soils at different pH. Soil Biol Biochem 29:1033–1042

Andersson M, Michelsen A, Jensen M, Kjøller A (2004) Tropical savannah woodland: effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide. Soil Biol Biochem 36:849–858

Ayanaba A, Tuckwell SB, Jenkinson DS (1976) The effects of clearing and cropping on the organic reserves and biomass of tropical forest soils. Soil Biol Biochem 8:519–525

Babiuk LA, Paul EA (1970) The use of fluorescein isothiocyanate in the determination of the bacterial biomass of grassland soil. Can J Microbiol 16:57–62

Balota EL, Filho AC, Andrade DS, Dick RP (2004) Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Till Res 77:137–145

Bastida F, Zsolnay A, Hernández T, García C (2008) Past, present and future of soil quality indices: a biological perspective. Geoderma 147:159–171

Basu S, Behera N (1993) The effect of tropical forest conversion on soil microbial biomass. Biol Fertil Soils 16:302–304

Bationo A, Kihara J, Vanlauwe B, Waswa B, Kimetu J (2007) Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric Syst 94:13–25

Behera N, Sahani U (2003) Soil microbial biomass and activity in response to *Eucalyptus* plantation and natural regeneration on tropical soil. For Ecol Manage 174:1–11

Bhattacharyya P, Chakrabarti K, Chakraborty A (2005) Microbial biomass and enzyme activities in submerged rice soils amended with municipal solid waste compost and decomposed cow manure. Chemosphere 60:1513–1522

Bilgo A, Masse D, Sall S, Serpantie G, Chotte JL, Hien V (2007) Chemical and microbial properties of semiarid tropical soils of short-term fallows in Burkina Faso, West Africa. Biol Fertil Soils 43:313–320

Bossio DA, Girvan MS, Verchot L, Bullimore J, Borelli T, Albrecht A, Scow KM, Ball AS, Pretty JN, Osborn AM (2005) Soil microbial community response to land use change in an agricultural landscape of Western Kenya. Microb Ecol 49:50–62

Brookes PC, Powlson DS, Jenkinson DS (1982) Measurement of microbial biomass phosphorus in soil. Soil Biol Biochem 14:319–329

Brookes PC, Landman A, Pruden G, Jenkinson DS (1985) Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method for measuring microbial biomass nitrogen in soil. Soil Biol Biochem 17:837–842

Bünemann EK, Bossio DA, Smithson PC, Frossard E, Oberson A (2004) Microbial community composition and substrate use in a highly weathered soil as affected by crop rotation and P fertilization. Soil Biol Biochem 36:889–901

Cantarutti RB et al (2002) The effect of grazing intensity and the presence of a forage legume on nitrogen dynamics in Brachiaria pastures in the Atlantic forest region of the south of Bahia, Brazil. Nutr Cycl Agroecosyst 64:257–271

Castillo X, Joergensen RG (2001) Impact of ecological and conventional arable management systems on chemical and biological soil quality indices in Nicaragua. Soil Biol Biochem 33:1591–1597

Cerri CEP, Coleman K, Jenkinson DS, Bernoux M, Victoria R, Cerri CC (2003) Modeling soil carbon from forest and pasture ecosystems of Amazon, Brazil. Soil Sci Soc Am J 67:1879–1887

Cerri CEP, Piccolo MC, Feigl BJ, Paustian K, Cerri CC, Victoria RL, Melillo JM (2006) Interrelationships among soil total C and N, microbial biomass, trace gas fluxes and internal N-cycling in soils under pasture of the Amazon region. J Sustain Agric 27:45–69

Chander K, Dyckmans J, Joergensen RG, Meyer B, Raubuch M (2001) Different sources of heavy metals and their long-term effects on soil microbial properties. Biol Fertil Soils 34:241–247

Cleveland CC, Liptzin D (2007) C:N:P stoichiometry in soil: is there a "Redfield ratio" for the microbial biomass. Biogeochemistry 85:235–252

Cleveland CC, Townsend AR, Schmidt SK, Constance BC (2003) Soil microbial dynamics and biogeochemistry in tropical forests and pastures, southwestern Costa Rica. Ecol Appl 13:314–326

Contin M, Todd A, Brookes PC (2001) The ATP concentrations in the soil microbial biomass. Soil Biol Biochem 33:701–704

Craswell ET, Lefroy RDB (2001) The role and function of organic matter in tropical soils. Nutr Cycl Agroecosyst 61:7–18

Das P, Pal R, Chowdhury A (2007) Effect of novaluron on microbial biomass, respiration, and fluorescein diacetate-hydrolyzing activity in tropical soils. Biol Fertil Soils 44:387–391

de Oliveira OC, de Oliveira IP, Alves BJR, Urquiaga S, Boddey RM (2004) Chemical and biological indicators of decline/degradation of *Brachiaria* pastures in the Brazilian Cerrado. Agric Ecosyst Environ 103:289–300

Diels J, Vanlauwe B, van der Meersch MK, Sanginga N, Merckx R (2004) Long-term soil organic carbon dynamics in a subhumid tropical climate: ^{13}C data in mixed C_3/C_4 cropping and modeling with ROTHC. Soil Biol Biochem 36:1739–1750

Dilly O (2005) Microbial energetics in soils. In: Buscot F, Varma A (eds) Microorganisms in soils: Roles in genesis and functions. Springer, Berlin, pp 123–138

Dilly O, Blume HP, Sehy U, Jimenez M, Munch JC (2003) Variation of stabilised, microbial and biologically active carbon and nitrogen in soil under contrasting land use and agricultural management practices. Chemosphere 52:557–569

Dinesh R (2004) Long-term effects of leguminous cover crops on microbial indices and their relationships in soils of a coconut plantation of a humid tropical region. J Plant Nutr Soil Sci 167:189–195

Dinesh R, Chaudhuri SG, Ganeshamurthy AN, Dey C (2003) Changes in soil microbial indices and their relationships following deforestation and cultivation in wet tropical forests. Appl Soil Ecol 24:17–26

Dinesh R, Chaudhuri SG, Sheeja TE (2004a) Soil biochemical and microbial indices in wet tropical forests: effects of deforestation and cultivation. J Plant Nutr Soil Sci 167:24–32

Dinesh R, Suryanarayana MA, Chaudhuri SG, Sheeja TE (2004b) Long-term influence of leguminous cover crops on the biochemical properties of a sandy clay loam Fluventic Sulfaquent in a humid tropical region of India. Soil Till Res 77:69–77

Dinesh R, Chaudhuri SG, Sheeja TE (2006) ATP levels and adenylate energy charge in soils of mangroves in the Andamans. Curr Sci 90:1258–1263

Djajakirana G, Joergensen RG, Meyer B (1996) Ergosterol and microbial biomass relationship in soil. Biol Fertil Soils 22:299–304

Duah-Yentumi S, Rønn R, Christensen S (1998) Nutrients limiting microbial growth in a tropical forest soil of Ghana under different management. Appl Soil Ecol 8:19–24

Duponnois R, Founoune H, Masse D, Pontanier R (2005) Inoculation of *Acacia holosericea* with ectomycorrhizal fungi in a semiarid site in Senegal: growth response and influences on the mycorrhizal soil infectivity after 2 years plantation. For Ecol Manag 207:351–362

Dyckmans J, Chander K, Joergensen RG, Priess J, Raubuch M, Sehy U (2003) Adenylates as an estimate of microbial biomass C in different soil groups. Soil Biol Biochem 35:1485–1491

Fernandes SAP, Bettiol W, Cerri CC (2005) Effect of sewage sludge on microbial biomass, basal respiration, metabolic quotient and soil enzymatic activity. Appl Soil Ecol 30:65–77

Förster B, Muroya K, Garcia M (2006) Plant growth and microbial activity in a tropical soil amended with faecal pellets from millipedes and woodlice. Pedobiology 50:281–290

Galicia L, García-Oliva F (2004) The effects of C, N and P additions on soil microbial activity under two remnant tree species in a tropical seasonal pasture. Appl Soil Ecol 26:31–39

Galicia L, García-Oliva F (2008) Remnant tree effects on soil microbial carbon and nitrogen in tropical seasonal pasture in western Mexico. Eur J Soil Biol 44:290–297

Geissen V, Morales Guzman G (2006) Fertility of tropical soils under different land use system — a case study of soils in Tabasco, Mexico. Appl Soil Ecol 31:169–178

Gijsman AJ, Oberson A, Friesen DK, Sanz JI, Thomas RJ (1997) Nutrient cycling through microbial biomass under rice-pasture rotations replacing native savanna. Soil Biol Biochem 29:1433–1441

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal — a review. Biol Fertil Soils 35:219–230

Gnankambary Z, Ilstedt U, Nyberg G, Hien V, Malmer A (2008) Nitrogen and phosphorus limitation of soil microbial respiration in two tropical agroforestry parklands in the south-Sudanese zone of Burkina Faso: the effects of tree canopy and fertilization. Soil Biol Biochem 40:350–359

Grant WD (1979) Cell wall teichoic acid as a reserve phosphate source in *Bacillus subtilis*. J Bacteriol 137:35–68

Groffman PM, McDowell WH, Myers JC, Merriam JL (2001) Soil microbial biomass and activity in tropical riparian forests. Soil Biol Biochem 33:1339–1348

Haron K, Brookes PC, Anderson JM, Zakaria ZZ (1998) Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* Jacq.) plantations, West Malaysia. Soil Biol Biochem 30:547–552

Henrot J, Robertson GP (1994) Vegetation removal in two soils of the humid tropics: effect on microbial biomass. Soil Biol Biochem 26:111–116

Islam KR, Weil RR (2000) Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agric Ecosyst Environ 79:9–16

Izquierdo I, Caravaca F, Alguacil MM, Roldan A (2003) Changes in physical and biological soil quality indicators in a tropical crop system (Havana, Cuba) in response to different agroecological management practices. Environ Manag 32:639–645

Jastrow JD, Amonette JE, Bailey VL (2007) Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. Clim Change 80:5–23

Jenkinson DS (1988) The determination of microbial biomass carbon and nitrogen in soil. In: Wilson JR (ed) Advances in nitrogen cycling in agricultural ecosystems. CABI, Wallingford, pp 368–386

Jenkinson DS, Ayanaba A (1977) Decomposition of carbon-14 labeled plant material under tropical conditions. Soil Sci Soc Am J 41:912–915

Jenkinson DS, Ladd JN (1981) Microbial biomass in soil: measurement and turnover. In: Paul EA, Ladd JN (eds) Soil biochemistry, vol 5. Marcel Dekker, New York, pp 415–471

Jenkinson DS, Oades JM (1979) A method for measuring adenosine triphosphate in soil. Soil Biol Biochem 11:193–199

Jenkinson DS, Powlson DS (1976) The effects of biocidal treatments on metabolism in soil V. A method for measuring soil biomass. Soil Biol Biochem 8:209–213

Jenkinson DS, Hart PBS, Rayner JH, Parry LC (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bull 15:1–8

Jensen M, Michelsen A, Gashaw M (2001) Responses in plant, soil inorganic and microbial nutrient pools to experimental fire, ash and biomass addition in a woodland savanna. Oecologia 128:85–93

Jörgensen RG (1995) Die quantitative Bestimmung der mikrobiellen Biomasse in Böden mit der Chloroform-Fumigations-Extraktions-Methode. Gött Bodenkundl Ber 104:1–229

Joergensen RG (1996a) The fumigation-extraction method to estimate soil microbial biomass: calibration of the k_{EC} value. Soil Biol Biochem 28:25–31

Joergensen RG (1996b) Quantification of the microbial biomass by determining ninhydrin-reactive N. Soil Biol Biochem 28:301–306

Joergensen RG, Brookes PC (1990) Ninhydrin-reactive nitrogen measurements of microbial biomass in 0.5 M K_2SO_4 soil extracts. Soil Biol Biochem 22:1023–1027

Joergensen RG, Castillo X (2001) Interrelationships between microbial and soil properties in young volcanic ash soils of Nicaragua. Soil Biol Biochem 33:1581–1589

Joergensen RG, Emmerling C (2006) Human impact on soil organisms and on current measurement methods. J Plant Nutr Soil Sci 169:295–309

Joergensen RG, Mueller T (1996) The fumigation-extraction method to estimate soil microbial biomass: calibration of the k_{EN} value. Soil Biol Biochem 28:33–37

Joergensen RG, Wichern F (2008) Quantitative assessment of the fungal contribution to microbial tissue in soil. Soil Biol Biochem 40:2977–2991

Kaiser EA, Mueller T, Joergensen RG, Insam H, Heinemeyer O (1992) Evaluation of methods to estimate the soil microbial biomass and the relationship with soil texture and organic matter. Soil Biol Biochem 24:675–683

Kaonga ML, Coleman K (2008) Modelling soil organic carbon turnover in improved fallows in eastern Zambia using the RothC-26.3 model. For Ecol Manage 256:1160–1166

Li Y, Xu M, Zou X (2006a) Effects of nutrient additions on ecosystem carbon cycle in a Puerto Rican tropical wet forest. Global Change Biol 12:284–293

Li Y, Xu M, Zou X (2006b) Heterotrophic soil respiration in relation to environmental factors and microbial biomass in two wet tropical forests. Plant Soil 281:193–201

Lodge DJ, Ingham ER (1991) A comparison of agar film techniques for estimating fungal biovolumes in litter and soil. Agric Ecosys Environ 5:31–37

Luizao RCC, Bonde TA, Rosswall T (1992) Seasonal variation of soil microbial biomass – the effects of clearfelling a tropical rainforest and establishment of pasture in the central Amazon. Soil Biol Biochem 24:805–813

Lulu B, Insam H (2000a) Medium-term effects of a single application of mustard residues on soil microbiota and C content of vertisols. Biol Fertil Soils 31:108–113

Lulu B, Insam H (2000b) Effects of cropping systems and manuring on soil microbial and C status of a Vertisol in Ethiopia. Bodenkultur 51:107–114

Manna MC, Swarup A, Wanjari RH, Ravankar HN (2007) Long-term effects of NPK fertiliser and manure on soil fertility and a sorghum-wheat farming system. Aust J Exp Agric 47:700–711

Mao DM, Min YW, Yu LL, Martens R, Insam H (1992) Effect of afforestation on microbial biomass and activity in soils of tropical China. Soil Biol Biochem 24:865–872

Marschner P, Marino W, Lieberei R (2002) Seasonal effects on microorganisms in the rhizosphere of two tropical plants in a polyculture agroforestry system in Central Amazonia, Brazil. Biol Fertil Soils 35:68–71

Mazzarino MJ, Szott L, Jimenez M (1993) Dynamics of soil total C and N, microbial biomass, and water-soluble C in tropical agroecosystems. Soil Biol Biochem 25:205–214

Michelsen A, Andersson M, Jensen M, Kjøller A, Gashew M (2004) Carbon stocks, soil respiration and microbial biomass in fire-prone tropical grassland, woodland and forest ecosystems. Soil Biol Biochem 36:1707–1717

Montano NM, Garcia-Oliva F, Jaramillo VJ (2007) Dissolved organic carbon affects soil microbial activity and nitrogen dynamics in a Mexican tropical deciduous forest. Plant Soil 295: 265–277

Moore JC, McCann K, de Ruiter PC (2005) Modeling trophic pathways, nutrient cycling, and dynamic stability in soils. Pedobiologia 49:499–510

Motavalli PP, Discekici H, Kuhn J (2000) The impact of land clearing and agricultural practices on soil organic C fractions and CO_2 efflux in the Northern Guam aquifer. Agric Ecosyst Environ 79:17–27

Muhammad S, Müller T, Joergensen RG (2007) Compost and phosphorus amendments for stimulating microorganisms and maize growth in a saline Pakistani soil in comparison with a non-saline German soil. J Plant Nutr Soil Sci 170:745–751

Mulongoy K (1986) Microbial biomass and maize nitrogen uptake under a *Psophocarpus palustris* live-mulch grown on a tropical Alfisol. Soil Biol Biochem 18:395–398

Ndiaye D, Lepage M, Sall CE, Brauman A (2004) Nitrogen transformations associated with termite biogenic structures in a dry savanna ecosystem. Plant Soil 265:189–196

Ndour NYB, Baudoin E, Guisse A, Seck M, Khouma M, Brauman A (2008) Impact of irrigation water quality on soil nitrifying and total bacterial communities. Biol Fertil Soils 44:797–803

Nelson DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR (Eds.) Methods of soil analysis Part 2, 2nd edn. Agronomy Monograph 9. American Society of Agronomy, Madison, WI, pp 539–579

Nielsen JS, Joner EJ, Declerck S, Olsson S, Jacobsen I (2002) Phospho-imaging as a tool for visualisation and non-invasive measurement of P transport dynamics in arbuscular mycorrhiza. New Phytol 154:809–819

Nogueira MA et al (2006) Promising indicators for assessment of agroecosystems alteration among natural, reforested and agricultural land use in southern Brazil. Agric Ecosyst Environ 115:237–247

Northup BK, Brown JR, Holt JA (1999) Grazing impacts on the spatial distribution of soil microbial biomass around tussock grasses in a tropical grassland. Appl Soil Ecol 13:259–270

Oberson A, Joner EJ (2005) Microbial turnover of phosphorous in soil. In: Turner BL, Frossard E, Baldwin DS (eds) Organic phosphorous in the environment. CABI, Wallingford, pp 133–164

Oberson A, Friesen DK, Rao IM, Bühler S, Frossard E (2001) Phosphorus transformations in an Oxisol under contrasting land-use systems: the role of the soil microbial biomass. Plant Soil 237:197–210

Oehl F, Frossard E, Fließbach A, Dubois D, Oberson A (2004) Basal organic phosphorus mineralization in soils under different farming systems. Soil Biol Biochem 36:667–675

Olsson PA, Larsson L, Bago B, Wallander H, van Aarle IM (2003) Ergosterol and fatty acids for biomass estimation of mycorrhizal fungi. New Phytol 159:1–10

Powlson DS, Brookes PC, Christensen BT (1987) Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol Biochem 19:159–164

Prasad P, Basu S, Behera N (1995) A comparative account of the microbiological characteristics of soils under natural forest, grassland and cropfield from Eastern India. Plant Soil 175:85–91

Priess JA, Fölster H (2001) Microbial properties and soil respiration in submontane forests of Venezuelian Guyana: characteristics and response to fertilizer treatments. Soil Biol Biochem 33:503–509

Rabary B, Sall S, Letourmy P, Husson O, Ralambofetra E, Moussa N, Chotte JL (2008) Effects of living mulches or residue amendments on soil microbial properties in direct seeded cropping systems of Madagascar. Appl Soil Ecol 39:236–243

Rajashekhara Rao BK, Siddaramappa R (2008) Evaluation of soil quality parameters in a tropical paddy soil amended with rice residues and tree litters. Eur J Soil Biol 44:334–340

Rillig MC, Wright SF, Nichols KA, Schmidt WF, Torn MS (2001) Large contribution of arbuscular mycorrhizal fungi to soil carbon pools in tropical forest soils. Plant Soil 233:167–177

Sahani U, Behera N (2001) Impact of deforestation on soil physicochemical characteristics, microbial biomass and microbial activity of tropical soil. Land Degrad Dev 12:93–105

Sakamoto K, Oba Y (1994) Effect of fungal to bacterial biomass ratio on the relationship between CO_2 evolution and total soil microbial biomass. Biol Fertil Soils 17:39–44

Salamanca EF, Raubuch M, Joergensen RG (2002) Relationships between soil microbial indices in secondary tropical forest soils. Appl Soil Ecol 21:211–219

Salamanca EF, Raubuch M, Joergensen RG (2006) Microbial reaction of secondary tropical forest soils to the addition of leaf litter. Appl Soil Ecol 31:53–61

Salinas-García JR, de Velázquez-García J, Gallardo-Valdez M, Díaz-Mederos P, Caballero-Hernández F, Tapia-Vargas LM, Rosales-Robles E (2002) Tillage effects on microbial biomass and nutrient distribution in soils under rain-fed corn production in central-western Mexico. Soil Till Res 66:143–152

Sall SN, Masse D, Ndour NYB, Chotte JL (2006) Does cropping modify the decomposition function and the diversity of the soil microbial community of tropical fallow soil. Appl Soil Ecol 31:211–219

Saynes V, Hidalgo C, Etchevers JD, Campo JE (2005) Soil C and N dynamics in primary and secondary seasonally dry tropical forests in Mexico. Appl Soil Ecol 29:282–289

Scheller E, Joergensen RG (2008) Decomposition of wheat straw differing in N content in soils under conventional and organic farming management. J Plant Nutr Soil Sci 171:886–892

Shen H, Xu ZH, Yan XL (2001) Effect of fertilization on oxidizable carbon, microbial biomass carbon, and mineralizable carbon under different agroecosystems. Commun Soil Sci Plant Anal 32:1575–1588

Sierra J, Marbán L (2000) Nitrogen mineralization pattern of an oxisol of Guadeloupe, French West Indies. Soil Sci Soc Am J 64:2002–2010

Sierra J, Nygren P (2005) Role of root inputs from a dinitrogen-fixing tree in soil carbon and nitrogen sequestration in a tropical agroforestry system. Aust J Soil Res 43:667–675

Singh RS, Srivastava SC, Raghubanshi AS, Singh JS, Singh SP (1991) Microbial C, N and P in dry tropical savanna: effects of burning and grazing. J Appl Ecol 28:869–878

Srivastava SC, Lal SC (1994) Effects of crop growth and soil treatments on microbial C, N and P in dry tropical forest land. Biol Fertil Soils 17:109–117

Srivastava SC, Singh JS (1991) Microbial C, N and P in dry tropical forest soils: effects of alternate land-uses and nutrient flux. Soil Biol Biochem 23:117–124

Templer PH, Groffman PM, Flecker AS, Power AG (2005) Land use change and soil nutrient transformations in the Los Haitises region of the Dominican Republic. Soil Biol Biochem 37:215–225

Tian G (1998) Effect of soil degradation on leaf decomposition and nutrient release under humid tropical conditions. Soil Sci 163:897–906

Toledo-Aceves T, Garcia-Oliva F (2008) Effects of forest–pasture edge on C, N and P associated with *Caesalpinia eriostachys*, a dominant tree species in a tropical deciduous forest in Mexico. Ecol Res 23:271–280

Tornquist CG, Hons FM, Feagley SE, Haggar J (1999) Agroforestry system effects on soil characteristics of the Sarapiquí region of Costa Rica. Agric Ecosyst Environ 73:19–28

Torsvik V, Øvreås L (2007) Microbial phylogeny and diversity in soil. In: van Elsas JD, Jansson JK, Trevors JT (eds) Modern soil microbiology, 2nd edn. CRC Press, Boca Raton, FL, pp 23–54

Tripathi S, Kumari S, Chakraborty A, Gupta A, Chakrabarti K, Bandyapadhyay BK (2006) Microbial biomass and its activities in salt-affected coastal soils. Biol Fertil Soils 42:273–277

Turgay OC, Lumbanraja J, Yusnaini S, Nonaka M (2002) Effect of land degradation on soil microbial biomass in a hilly area of south Sumatra, Indonesia. Soil Sci Plant Nutr 48:769–774

Vance ED, Nadkarni NM (1990) Microbial biomass and activity in canopy organic matter and the forest floor of a tropical cloud forest. Soil Biol Biochem 22:677–684

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. Soil Biol Biochem 19:703–707

Villenave C, Bongers T, Ekschmitt K, Fernandes P, Oliver R (2003) Changes in nematode communities after manuring in millet fields in Senegal. Nematol 5:351–358

Villenave C, Ekschmitt K, Nazaret S, Bongers T (2004) Interactions between nematodes and microbial communities in a tropical soil following manipulation of the soil food web. Soil Biol Biochem 36:2033–2043

Vineela C, Wani SP, Srinivasarao C, Padmaja B, Vittal KPR (2008) Microbial properties of soils as affected by cropping and nutrient management practices in several long-term manurial experiments in the semi-arid tropics of India. Appl Soil Ecol 40:165–173

Waldrop MP, Balser TC, Firestone MK (2000) Linking microbial community composition to function in a tropical soil. Soil Biol Biochem 32:1837–1846

Wardle DA (1998) Controls of temporal variability of the soil microbial biomass: a global scale synthesis. Soil Biol Biochem 30:1627–1637

Wick B, Kühne RF, Vlek PLG (1998) Soil microbiological parameters as indicators of soil quality under improved fallow management systems in south-western Nigeria. Plant Soil 202:97–107

Winding A, Hund-Rinke K, Rutgers M (2005) The use of microorganisms in ecological soil classification and assessment concepts. Ecotoxicol Environ Safety 62:230–248

Witt C, Gaunt JL, Galicia CC, Ottow JCG, Neue HU (2000) A rapid chloroform-fumigation extraction method for measuring microbial biomass carbon and nitrogen in flooded rice soils. Biol Fertil Soils 30:510–519

Wu J, Joergensen RG, Pommerening B, Chaussod R, Brookes PC (1990) Measurement of soil microbial biomass C — an automated procedure. Soil Biol Biochem 22:1167–1169

Wu J, He ZL, Wei WX, O'Donnell AG, Syers JK (2000) Quantifying microbial biomass phosphorus in acid soils. Biol Fertil Soils 32:500–507

Xu X, Han L, Wang Y, Inubushi K (2007) Influence of vegetation types and soil properties on microbial biomass carbon and metabolic quotients in temperate volcanic and tropical forest soils. Soil Sci Plant Nutr 53:430–440

Yavitt JB, Wieder RK, Wright SJ (1993) Soil nutrient dynamics in response to irrigation of a Panamanian tropical moist forest. Biogeochemistry 19:1–25

Zhang H, Zhang GL (2003) Microbial biomass carbon and total organic carbon of soils as affected by rubber cultivation. Pedosphere 13:353–357

Zhang H, Zhang GL, Zhao YG, Zhao WJ, Qi ZP (2007) Chemical degradation of a Ferralsol (Oxisol) under intensive rubber (*Hevea brasiliensis*) farming in tropical China. Soil Till Res 93:109–116

Zunino H, Borie F, Aguielera S, Martin JP, Haider K (1982) Decomposition of ^{14}C-labeled glucose, plant and microbial products and phenols in volcanic ash-derived soils of Chile. Soil Biol Biochem 14:37–43

http://www.springer.com/978-3-642-05075-6

Soil Biology and Agriculture in the Tropics
Dion, P. (Ed.)
2010, XIII, 350 p. 21 illus., Hardcover
ISBN: 978-3-642-05075-6