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REGULAR ARTICLE

Quantifying effects of different agricultural land uses on soil microbial biomass and activity in Brazilian biomes: inferences to improve soil quality

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Abstract Maintenance of soil quality is a key component of agriculture sustainability and a main goal of most farmers, environmentalists and government policymakers. However, as there are no parameters or methods to evaluate soil quality directly, some attributes of relevant soil functions are taken as indicators; lately, an increase in the use of soil microbial parameters has occurred, and their viability as indicators of proper land use has been highlighted. In this study we performed a meta-analysis of the response ratios of several microbial and chemical parameters to soil disturbance by different land uses in the Brazilian biomes. The studies included native forests, pastures and perennial and annual cropping systems. The introduction of agricultural practices in all biomes covered previously with natural vegetation profoundly affected microbial biomass-C (MB-C)—with an overall decrease of 31%. Annual crops most severely reduced microbial biomass and soil organic C, with an average decrease of 53% in the MB-C. In addition, the MB-C/TSOC (total soil organic carbon) ratio was significantly decreased with the transformation of forests to perennial plantation (25%), pastures (26%), and annual cropping (20%). However, each biome reacted differently to soil disturbance, i.e., decreases in MB-C followed the order of Cerrado>Amazon>Caatinga>Atlantic Forest. In addition, the Cerrado appeared to have the most fragile soil ecosystem because of lower MB-C/TSOC and higher $q\mathrm{CO_2}$. Unfortunately, the Cerrado and the Amazon, demonstrated by our study as the most fragile biomes, have been subjected to the highest agronomic pressure. The results reported here may help to infer the best land-use strategies to improve soil quality and achieve agriculture sustainability. The approach can also be very useful to monitor soil quality in other tropical and subtropical biomes.

Keywords Brazilian biomes · Deforestation · Meta-analyses · Land use change · Soil organic matter

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Introduction

Brazil is the third agribusiness leader worldwide, following European Union and United States (WTO 2009). However, while agriculture development empowers Brazilian´s economy, there are often doubts about its impacts on the biodiversity. The agribusiness sector (with a minor contribution from urbanization, forestation and mining) is spread in all biomes of the country, taking at least 88.3% of the area in the Atlantic Forest (Ribeiro et al. 2009), 78.8% of the Caatinga (Franca-Rocha et al. 2007), 25% of the Pampas (Overbeck et al. 2007), 39.5% of the Cerrado (Sano et al. 2008), 44% of the Pantanal (Harris et al. 2006) and 9.3% of the Amazon (Santos et al. 2007). Following trends from the last decades, the agricultural activities will expand and claim more land. One could prevent that native areas are cleared for agriculture by promoting soil quality and sustaining an effective production in the already occupied land.

By definition, soil quality is the continued capacity of the soil to function as a vital living system, within ecosystems and land-use boundaries, to sustain biological productivity, promote air and water quality, and maintain plant, animal and human health (Doran and Parkin 1994; Karlen et al. 1997; Sparling 1997; Seybold et al. 1999). Maintenance of soil quality has been considered as a key component of agriculture sustainability and a goal of most farmers, environmentalists and government policymakers (e.g. Sherwood and Uphoff 2000; Tóth et al. 2007). As there are no parameters or methods to evaluate soil quality directly, some attributes of relevant soil functions are taken as indicators. One of the most promising indicators is soil microbial biomass-C (MB-C), as it has a faster turnover than total soil organic matter (SOM) (Jenkinson and Ladd 1981; Sparling 1997) and shows more-rapid responses to soil environmental changes than other soil physical-chemical properties or crop productivity (e.g. Wardle 1992; Balota et al. 1998; Roscoe et al. 2006; Franchini et al. 2007; Pereira et al. 2007; Hungria et al. 2009; Kaschuk et al. 2010).

Soil microorganisms play crucial roles in key processes such as mineralization, immobilization, nutrient foraging and acquirement (e.g. by arbuscular mycorrhizal fungi and diazotrophic bacteria) and decomposition of xenobiotics, resulting in profound effects on soil chemical and physical properties (e.g. Wardle 1992; Sparling 1997; Seybold et al. 1999). One limitation of using MB-C as an indicator is that we are still far from establishing precise values that can be promptly interpreted in terms of soil-quality changes. Different values may result from the fact that MB-C is affected by environmental conditions, with responses varying with soil type (Pfenning et al. 1992), SOM content (Roscoe et al. 2006), stage of crop development (Perez et al. 2004; Hungria et al. 2009), season (Theodoro et al. 2003), among others. However, there is evidence that temporal variability in microbial biomass remains constant with increasing disturbance levels (Wardle 1998; Hungria et al. 2009), giving support to the adoption of MB-C as a parameter of soil quality.

As MB-C varies greatly with vegetation, in a survey of several Brazilian ecosystems under native vegetation, the absolute values—estimated by the fumigation-extraction method (FE)—varied from 101 to 1,520 mg C kg^{-1} soil (Kaschuk et al. 2010). Variability may also result from different methods of evaluating MB-C (e.g. Jenkinson and Powlson 1976; Vance et al. 1987), mainly associated with the coefficient of conversion from CO_2 emission to the microbial biomass, still not well determined for many soils, especially in the tropics (Roscoe et al. 2006). However, a valid approach in studies of soil quality is to compare the ratio of change of microbial biomass data obtained from a native or secondary forest and agricultural fields under similar experimental conditions, including the analytical method, soil type and temporal scale (e.g. Sparling 1997; Kaschuk et al. 2010).

In this study, we tested the degree to which agricultural uses affect the MB-C in native soils of Brazilian biomes by performing a meta-analysis, which considered native vegetation as control and agricultural uses (perennial, annual cropping and pastures) as the treatments. In addition, further land uses with proper controls were also investigated. Both treatments and control results were obtained under similar experimental conditions. Our analysis should allow us to draw conclusions on maintenance of soil quality under different soil use managements, as well as to raise hypotheses about soil susceptibility to agricultural uses in different biomes. The results reported here are also important to establish land-use strategies that will help to improve agriculture sustainability in other tropical countries.

Material and methods

Brazilian biomes and types of land use considered in the meta-analysis

We searched for reports of microbial biomass-C (MB-C) performed with the methodology proposed by Jenkinson and Powlson (1976), Vance et al. (1987) and minor modifications of these methods in at least two types of land use in one of the Brazilian biomes. Data were gathered in scientific and other published papers, conference proceedings and university theses through "Web of Science," "Scopus" and "Google Scholar." We included publications that have not been peer-reviewed to circumvent the problem of significant-response bias (i.e. studies showing significant results are more likely to be published than those showing insignificant responses to treatments) (Gurevitch and Hedges 2001). The key words were: "soil microbial biomass", "Brazil" and "soil management," with the respective translations to Portuguese "biomassa microbiana do solo", "Brasil" and "manejo do solo." We also gathered data on: metabolic quotient (qCO$_2$), total soil organic C (TSOC), MB-C/TSOC ratio, soil organic matter (SOM), microbial biomass-N (MB-N), cation-exchange capacity (CEC) and total soil phosphorus content in the soil (TSP). The literature search considered studies since 1992 and ended on May 31st 2010.

We included only the studies performed in Brazil, categorized according to their respective biomes. Where the authors did not define their ecosystems, we checked the locations of the studies on the map (Fig. 1) to determine the biomes.

According to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA 2010), there are seven biomes in Brazil: Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas, Pantanal and Coast. We did not include the Coast (Costeiros), a biome characterized by swamps, dunes, islands, reefs and other sea related ecosystems, because the use of agriculture in this biome is low and when cultivated the studies usually classify the biome as Atlantic Forest. The main characteristics of *each biome* (Portuguese nomenclature in parentheses) considered in this study are described below. Numerical information is provided in Table 1.

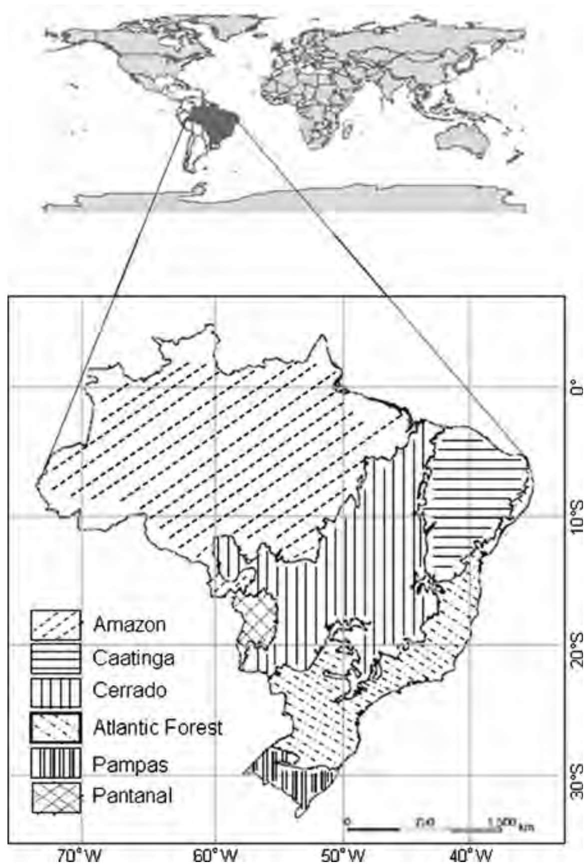

Fig. 1 The Brazilian biomes (IBGE 2004)

1. *Amazon (Amazônia)*: The Amazon rainforest, situated in a plain of 130 to 200 m in altitude, with variable soil clay contents, comprises land forest that is never flooded and by flooded forests, open grasslands, savannahs and swamps ("várzeas" and "igapós"). Traditionally it is farmed by shifting cultivation: a plot of forest is slashed, economical valuable trees are removed, residual vegetation is burnt and the land is farmed for a few years. When soil fertility and agricultural productivity have decreased to undesirable levels, the area is left for a restorative fallow of 4 to 8 years and the farmer slashes a new plot of forest (Sampaio et al. 2003).
2. *Cerrado (Cerrado, Cerrados)*: The Cerrado biome is comprised of savannahs and characterized by a gradient of grassland, savannah and forest, interspersed with riparian or gallery forests, patches of semi-deciduous forest, swamp and marshes (Ruggiero et al. 2002). Until the 1970s, it was used for wood extraction, beef-cattle ranching or upland rice (*Oryza sativa* L.) production, but new technologies now allow cropping such that about 40% of the original area has been deforested (Sano et al. 2008) and most grains produced in the country come from the Cerrado, e.g. 55% of the soybean [*Glycine max* (L.) Merr.] and 76% of the cotton (*Gossypium hirsutum* L.) (Embrapa 2009).
3. *Atlantic Forest (Mata Atlântica)*: This biome is composed of diverse ecosystems due to variability

Table 1 Total land area occupied by anthropogenic uses in Brazilian biomes.

Biome	Area in Brazilian Territory (km^2)	% of the Brazilian Territory	Area occupied (% of the biome area)	Reference
Amazon	4,196,943	49	9.3	Santos et al. (2007)
Atlantic	1,110,182	13	88.3	Ribeiro et al. (2009)
Caatinga	844,453	10	78.8	Franca-Rocha et al. (2007)
Cerrado	2,036,448	24	39.5	Sano et al. (2008)
Pampas	176,496	2	25.0	Overbeck et al. (2007)
Pantanal	150,355	2	44.0	Harris et al. (2006)

Occupied areas are mostly used for farming (cattle ranching and agriculture), but also for urbanization, exotic forestation and mining. Cultivated pastures for cattle ranching occupy 75 and 67% of the occupied areas in the Amazon and Cerrados biome, respectively. Occupied area in Pampas is certainly much higher because less than 0.5% of this biome is preserved within conservation unities; the figure of 25% in this table refers to the conversion of natural grassland into other land uses (e.g. agriculture and forestation) (Overbeck et al. 2007)

in soil type, landscape and climate characteristics. It is highly populated—about 120 million people—and is the most deforested biome. Estimates indicate that only ~12% of the region remains under natural vegetation (Ribeiro et al. 2009).

4. *Caatinga (Caatinga)*: Caatinga is xeric shrubland and thorn forest, subject to intermittent periods of drought. Despite unfavorable conditions, it supports 27 million people and thus only 22% of the area is free of anthropogenic influence (Franca-Rocha et al. 2007).
5. *Pantanal*: is the largest tropical wetland in the world, subject to seasonal inundation and desiccation. Soils range from high levels of sand in higher areas to higher amounts of clay and silt in riverine areas. Agricultural land is mostly used for cattle raising (IBAMA 2010).
5. *Southern Fields "Pampas" (Pampas, Campos Sulinos)*: This biome comprises natural grasslands with islands of araucaria forest [*Araucaria angustifolia* (Bertol.) Kuntze] (a variation of Atlantic Forest) (IBAMA 2010). The grassland ecosystems are determined by the soil characteristics rather than climate. The succession from grassland to shrubs vegetation is frequently prevented by cattle grazing and burning.

The following *types of land use* were included in the meta-analysis:

1. *Native forest:* Native areas under natural vegetation of a given biome that have not been used for anthropogenic purposes. Natural grassland or forest areas (e.g. in the Caatinga, Maia et al. 2007) being grazed by cattle were considered as pastures.
2. *Perennial plantation:* Fruit trees such as coffee (*Coffea arabica* L.), citrus (*Citrus* spp.), grape (*Vitis* spp.), cocoa (*Theobroma cacao* L.), cupuaçu (*Theobroma grandiflorum* Willd. ex Spreng.); fiber trees such as eucalyptus (*Eucalyptus* spp.), and pine (*Pinus elliottii* Engelm.); and sugar cane (*Saccharum* spp.). One study reported the effects of reforestation with native trees (Baretta et al. 2005).
3. *Pasture:* Cultivated pasture or natural grassland consistently used for grazing. We have included neither annual pastures that have been rotated with cropping systems (e.g. Mercante et al. 2004a), nor natural grasslands used for other than livestock or located in conservation areas (e.g. Nogueira et al. 2006).
4. *Annual cropping:* Various crop-management practices (e.g. organic and conventional farming, monocropping and crop rotation) and soil tillage (e.g. no-tillage, conventional tillage, minimum tillage or field cultivator).

Procedures for the meta-analysis

The information needed for the meta-analyses included: mean $\left(\overline{X}\right)$, standard deviation of the mean $\left(SD_{\overline{X}}\right)$ and number of replicates (n). The unities of the parameters in two comparable treatments were not important because they were canceled out during the calculations. We excluded studies with fewer than three field samples, even if reported means were obtained from three analytical replicates.

When the standard deviation was not reported, we gathered the coefficient of variation ($CV\%$) or standard error ($SE_{\overline{X}}$) and calculated $SD_{\overline{X}}$ with the following equations:

$$SD_{\overline{X}} = \frac{CV\%}{100} \cdot \overline{X} \tag{1}$$

$$SD_{\overline{X}} = SE_{\overline{X}} \cdot \sqrt{n} \tag{2}$$

For studies in which neither SD, SE nor $CV\%$ were reported, we calculated the variability ($CV\%$) of all means for that type of land use and biome, and used that variability multiplied by 1.5 to overcome problems of underestimation. We then obtained the $SD_{\overline{X}}$ according to Eq. 1.

The meta-analysis requires that measurements are independent one from another. Therefore, when a given study measured MB-C several times during one experiment (e.g. at different stages of development of a given crop), we considered only the last measurement. However, if the measurements were taken in the same area and land use but in different years or seasons (e.g. during dry and wet seasons), we considered the last measurement realized in each season or year. In many experiments, MB-C was measured in several soil layers; we have only considered the first top layer of 0–20 cm, and sometimes, only layers of 0–5 and 0–10 cm. The effects of depth on the MB-C and TSOC were cancelled, because the layer chosen was always similar in both the treatment and the control.

Although $q\mathrm{CO_2}$ and the MB-C/TSOC ratio are parameters dependent on MB-C, we considered them as independent in this study. In fact, $q\mathrm{CO_2}$ measures the respiratory efficiency of the microbial biomass, and the MB-C/TSOC ratio evaluates the C being immobilized by the microbial biomass.

For the data analysis, the first two groups of means—one representing the control and the other the experimental group—and the respective standard deviations were arranged in columns in Microsoft Excel® worksheets. The control was defined as the treatment causing less soil disturbance, whereas the experimental treatment was related to greater soil disturbance. The experimental/control groups were defined as follows: perennial plantation/native forest; pasture/native forest; annual cultivation/native forest; annual cultivation/perennial plantation; and annual cultivation/pasture,

We then calculated the log response ratio (lr, Eq. 3) and the variance in the changes from control to experimental groups (v_{ij}, Eq. 4) (Hedges et al. 1999; Rosenberg et al. 2000; Gurevitch and Hedges 2001), as follows:

$$lr = \ln \frac{\overline{X}_{ij}^{E}}{\overline{X}_{ij}^{C}} \tag{3}$$

$$v_{ij} = \frac{\left(SD_{ij}^{E}\right)^2}{N_{ij}^{E}\left(\overline{X}_{ij}^{E}\right)^2} + \frac{\left(SD_{ij}^{C}\right)^2}{N_{ij}^{C}\left(\overline{X}_{ij}^{C}\right)^2} \tag{4}$$

where: $\overline{X}_{ij}^{E}$ is the mean of the experimental group, $\overline{X}_{ij}^{C}$ is the mean of the control group, SD_{ij}^{E} is the standard deviation of the data in the experimental group, SD_{ij}^{C} is the standard deviation of the data in the control group, N_{ij}^{E} is the total number of data points in the experimental group and N_{ij}^{C} is the total number of data points in the experimental group.

The values of lr and v_{ij} were imported to the statistical software package MetaWin 2.0 (Rosenberg et al. 2000). MetaWin performed further variance analyses considering the mixed-model. It also used the reciprocal of the variance of each lr as the weight to estimate the 95% confidence intervals (CI). The values of lr were reverted to their exponent ($R = e^{lr}$). When reading the output of the meta-analysis, one should regard the response ratio (R) significantly positive if the lower limit of the 95% CI was larger than 1, and negative if the upper limit of the 95% CI was smaller than 1. If the lower 95% CI was lower than 1 and the upper confidence interval higher than 1, R was non-significantly different from 1. If there was no overlapping in the 95% CI of different categories (biomes and treatments), one should regard the differences in response ratios as statistically significant.

Results

Considering all Brazilian biomes and 95% of confidence interval (CI) for statistical inference, the meta-analysis allowed to reach the conclusion that any kind of soil disturbance in areas under native vegetation surveyed in this study severely reduced microbial biomass C (MB-C) (Table 2). The meta-analysis revealed significant decreases with the displacement

Table 2 Meta-analysis of the effects of agronomical uses on the soil microbial biomass-C (MB-C), total soil organic C (TSOC), the ratio of MB-C to TSOC and the metabolic quotient (qCO_2) in different biomes of Brazil

	MB-C			TSOC			MB-C/TSOC			qCO_2		
	R	95% CI	*n*	*R*	95% CI	*n*	*R*	95% CI	*n*	*R*	95% CI	*n*
Perennial Plantation / Forest												
Amazon	0.61	0.36–1.04	1*	1.08	0.82–1.41	1*	n.a.			n.a		
Atlantic Forest	0.68	0.55–0.84	20	0.65	0.53–0.79	15	1.07	0.77–1.49	10	1.25	0.73–2.13	5
Caatinga	1.16	0.78–1.73	9	0.82	0.68–0.99	9	1.43	0.94–2.19	9	0.95	0.56–1.59	5
Cerrado	0.76	0.47–1.23	14	0.86	0.78–0.95	8	1.14	0.76–1.71	5	0.82	0.17–3.91	2*
Pantanal	n.a.**			n.a.			n.a.			n.a.		
Average	0.79	0.67–0.93	44	0.75	0.68–0.84	33	1.20	1.00–1.45	24	1.01	0.79–1.29	12
Pasture / Forest												
Amazon	0.91	0.81–1.03	29	1.02	0.78–1.34	12	0.52	0.25–1.08	1*	1.50	0.80–2.81	1*
Atlantic Forest	0.98	0.64–1.51	12	0.73	0.61–0.89	8	1.04	0.70–1.53	6	1.69	0.73–3.92	5
Caatinga	0.47	0.22–1.00	5	0.79	0.59–1.06	5	0.98	0.64–1.51	5	1.01	0.53–1.94	5
Cerrado	0.61	0.51–0.74	45	0.93	0.83–1.05	20	0.79	0.61–1.02	26	2.46	1.30–4.66	23
Pantanal	0.30	0.23–0.70	4	0.41	0.29–0.59	4	0.68	0.34–1.34	4	3.15	1.75–5.68	4
Average	0.73	0.65–0.81	95	0.84	0.76–0.92	49	0.84	0.72–1.00	42	2.14	1.43–3.21	38
Annual cropping / Forest												
Amazon	0.47	0.23–0.96	3	0.92	0.74–1.16	1*	n.a.			1.90	0.07–54.3	2
Atlantic Forest	0.58	0.49–0.68	28	0.58	0.52–0.66	27	0.95	0.77–1.17	14	1.05	0.79–1.40	10
Caatinga	0.48	0.32–0.71	4	0.74	0.55–0.99	4	0.65	0.44–0.97	4	1.45	0.83–2.54	4
Cerrado	0.46	0.43–0.49	145	0.97	0.82–1.15	48	0.70	0.65–0.77	80	1.51	1.20–1.89	104
Pantanal	n.a.			n.a.			n.a.			n.a.		
Average	0.47	0.44–0.51	180	0.80	0.72–0.91	80	0.72	0.67–0.78	98	1.47	1.19–1.81	120
Annual cropping / Perennial Plantation												
Amazon	0.62	0.39–0.97	1*	0.86	0.67–1.09	1*	n.a.			n.a.		
Atlantic Forest	0.52	0.33–0.81	13	0.75	0.57–0.98	13	0.72	0.34–1.53	8	1.00	0.34–2.94	3
Caatinga	n.a.			n.a.			n.a.			n.a.		
Cerrado	1.18	0.48–2.89	5	0.90	0.71–1.13	5	1.00	0.17–5.71	2	n.a.		
Pantanal	n.a.			n.a.			n.a.			n.a.		
Average	0.65	0.47–0.91	19	0.79	0.66–0.95	19	0.77	0.43–1.37	10	1.00	0.34–2.94	3
Annual cropping / Pasture												
Amazon	n.a.			n.a.			n.a.			n.a.		
Atlantic Forest	0.68	0.52–0.88	9	0.80	0.57–1.12	8	1.04	0.08–13.6	2	n.a.		
Caatinga	0.76	0.43–1.32	1*	0.65	0.52–0.81	1*	1.17	0.67–2.04	1*	1.80	1.09–2.99	1*
Cerrado	0.93	0.80–1.08	52	0.98	0.84–1.12	22	1.03	0.82–1.29	37	0.53	0.32–0.86	42
Pantanal	n.a.			n.a.			n.a.			n.a.		
Pampas	0.69	0.58–0.81	14	0.80	0.68–0.92	14	n.a.			n.a.		
Average	0.83	0.76–0.89	76	0.87	0.80–0.96	45	1.03	0.83–1.28	40	0.54	0.38–0.88	43

References of the meta-analysis are given in the reference list under the heading "References used on the meta-analyses"

'*R*' is the response ratio, '95%CI' is the confidence intervals at $P<0.95\%$ for the *R* to be valid, and '*n*' is the number of data points. If *R* and the lower 95%CI are larger than 1, then the response is significantly positive; if *R* and the upper 95%CI are smaller than 1, then the response is significantly negative

* indicates the analysis based on the fixed model, otherwise random model

** indicates data not available

of natural forests by either perennial crops (Response ratio, R=0.79) or pastures (R=0.73), and the most drastic effect occurred with the transformation of forests to annual crops, decreasing MB-C by an average of 53% (R=0.47, CI=0.44–0.51). On average, replacement of perennial plantations by annual crops decreased MB-C by 35% (R=0.65, CI=0.47–0.91), while with the displacement of pasture by annual crops the decrease was of 17% (R=0.83, CI=0.76–0.89) (Table 2).

Analyzing each biome, perennial crops significantly decreased MB-C of soils under native vegetation in the Atlantic Forest (R=0.68), but had no effects in the Amazon (R=0.61), Caatinga (R=1.16) and Cerrado (R=0.76) (Table 2). Pasture introduction in areas under forest affected negatively MB-C mainly in the Cerrado (0.61, CI=0.51–0.74) and in the Pantanal (R=0.30, CI=0.23–0.70), but no significant effects were observed in the Amazon (R=0.91, CI=0.81–1.03), Atlantic Forest (R=0.98, CI=0.64–1.51) and Caatinga (R=0.47, CI=0.22–1.00), even though there was a reduction in MB-C of 53% in this last biome. From these data we may conclude that, despite the similarity of negative effects observed with the replacement of forests by perennial crops or pastures, the effects were more drastic with the introduction of perennial plants. On the other hand, MB-C in the Cerrado soils decreased by 32% with the transformation of native vegetation to pastures, while in the other biomes the effects were statistically non-significant. Finally, although negative effects of displacement of natural forests by annual cultivation were observed in all biomes, it is noteworthy that, considering the 95% CI, the response ratios in the Cerrado (R=0.46, CI=0.43–0.49) were lower than in the Atlantic Forest (R=0.58, CI=0.49–0.68) (Table 2).

The negative effects of replacement of perennial plantation by annual cropping on MB-C were significant in the Amazon (R=0.62, CI=0.39–0.97) and in the Atlantic Forest (R=0.52, CI=0.33–0.0.81), but not in the Cerrado (R=1.18, CI=0.48–2.89) (Table 2). In addition, replacement of cultivated pasture by annual cropping decreased MB-C significantly in the Atlantic Forest (R=0.68, CI=0.52–0.88), but not in the Caatinga and the Cerrado. In the Pampas, where cattle is raised on native grasses, MB-C was decreased by 31% under annual crops (Table 2).

Under perennial plantations, the total soil organic C (TSOC) of native forest soils was significantly reduced by an average of 25%, and the most drastic decrease was observed in the Atlantic Forest (R=0.65, CI=0.53–0.79), which was followed by the decreases in the Cerrado (R=0.82) and Caatinga (R=0.82) (Table 2). Likely due to only one data point, changes in TSOC of the Amazon biome were not significant. Although on average TSOC decreased by 16% with the replacement of forest by pastures, decreases in TSOC were only significant in the Atlantic Forest (R=0.73) and in the Pantanal (R=0.41). Similar results were obtained with the replacement of forests by annual crops, with a mean decrease of 20% in TSOC, and the most drastic effects occurred in the Atlantic Forest followed by the Caatinga. Changes of TSOC due to replacement of forest by annual cropping in the Amazon and in the Cerrado were not significant. On average significant decreases in TSOC were observed in the shift from perennial to annual cropping (21%) and from pasture to annual cropping (13%) (Table 2).

Although both MB-C and TSOC were reduced by soil disturbance, we found no consistent pattern of reduction or increase of the MB-C/TSOC ratios in the shift from native forest soils to perennial cropping or to pastures (Table 2). The only significant changes were decreases in the MB-C/TSOC ratio due to the replacement of forest by annual cropping (on average, R=0.72, CI=0.67–0.78; in the Caatinga, R=0.65 and in the Cerrado, R=0.70). Further decreases due to the replacement of perennial plantation or pasture by annual cropping were not significant (Table 2).

Considering all biomes, the mean response ratios of the metabolic quotient ($q\text{CO}_2$) resulting from transformation from forests to pastures were significantly larger than 1 (R=2.14) (Table 2). Taking the biomes individually, the increases were only significant in the Cerrado (R=2.46) and in the Pantanal (R=3.15), while changes in the Amazon (R=1.50), Atlantic Forest (R=1.69) and Caatinga (1.01) were not significant. On average, the $q\text{CO}_2$ increased 147% due to replacement of forest by annual cropping, but considering each biome individually, replacement of forest by annual cropping only caused increases in the $q\text{CO}_2$ in the Cerrado (R=1.51). No effects were observed with the change from perennial to annual cropping. Finally, a decrease was observed in the replacement of pastures by annual crops in the Cerrado (R=0.53, CI=0.32–0.86), but an increase was observed in the Caatinga (R=1.80, CI=1.09–2.00) (Table 2).

The overall effects of the shift from forests to perennial plantations on microbial biomass-N (MB-N) were non-significant; however, a strong negative response ratio was observed in the Atlantic Forest (R=0.47) (Table 3). Also, overall no effects were observed with pasture introduction to native areas, but a decrease was observed in the Cerrado (R=0.68). Annual cultivation caused the strongest effects in all biomes, with an emphasis on the very significant negative effects on the soils of the Atlantic Forest and Cerrado (R=0.22 and R=0.33, respectively). Finally, replacement of pastures by annual crops also had negative effects on MB-N in the Atlantic Forest (R=0.61) (Table 3).

Table 3 Meta-analysis of the effects of agronomical uses on the metabolic quotient (qCO_2), soil microbial biomass-N (MB-N) and cation exchange capacity (CEC) in different biomes of Brazil

Biome	MB-N			CEC			Total P		
	R	CI 95%	*n*	*R*	CI 95%	*n*	*R*	CI 95%	*n*
Perennial Plantation / Forest									
Amazon	n.a.			n.a.			n.a.		
Atlantic Forest	0.47	0.22–0.97	7	0.51	0.21–1.29	5	1.28	0.36–4.56	9
Caatinga	1.02	0.44–2.36	3	1.29	1.13–1.47	1*	7.06	4.98–10.0	1*
Cerrado	1.65	0.50–5.45	1*	0.76	0.42–1.41	2*	7.01	0.79–62.0	4
Pantanal	n.a.**			n.a.			n.a.		
Average	0.67	0.43–1.05	12	0.66	0.38–1.14	8	2.34	0.98–5.64	14
Pasture / Forest									
Amazon	0.87	0.64–1.20	10	0.78	0.62–0.98	1*	n.a.		
Atlantic Forest	1.12	0.70–1.80	6	0.94	0.87–1.02	1*	0.89	0.14–5.61	3
Caatinga	1.83	0.05–13.1	2*	n.a.			n.a.		
Cerrado	0.68	0.56–0.81	5	0.96	0.77–1.20	6	2.44	0.67–8.94	6
Pantanal	n.a.			n.a.			n.a.		
Average	0.97	0.78–1.20	24	0.95	0.82–1.11	8	1.74	0.74–4.04	9
Annual cropping / Forest									
Amazon	n.a.			n.a.			3.00	2.01–4.47	1*
Atlantic Forest	0.22	0.14–0.34	11	1.19	1.10–1.29	1*	8.17	1.97–33.9	5
Caatinga	0.89	0.32–2.48	1	0.58	0.43–0.79	1*	0.76	0.12–4.78	2*
Cerrado	0.33	0.29–0.38	33	0.99	0.77–1.28	14	4.47	2.66–7.51	26
Pantanal	n.a.			n.a.			n.a.		
Average	0.32	0.28–036	45	0.97	0.79–1.20	16	4.35	2.79–6.79	34
Annual cropping / Perennial Plantation									
Amazon	n.a.			n.a.			n.a.		
Atlantic Forest	0.60	0.02–24.2	3	1.17	1.08–1.27	1*	9.19	1.10–76.6	6
Caatinga	n.a.			n.a.			n.a.		
Cerrado	n.a.			0.95	0.83–1.08	1*	0.01	0–0.09	2
Pantanal	n.a.			n.a.			n.a.		
Average	0.60	0.02–24.2	3	1.06	0.72–1.71	2*	1.71	0.15–19.59	8
Annual cropping / Pasture									
Amazon	n.a.			n.a.			n.a.		
Atlantic Forest	0.61	0.40–0.91	5	1.13	1.04–1.22	1*	4.16	1.34–12.9	2
Caatinga	n.a.			1.63	1.19–2.22	1*	n.a.		
Cerrado	0.69	0.42–1.13	3	1.24	0.85–1.82	7	2.58	1.43–4.65	13
Pantanal	n.a.			n.a.			n.a.		
Pampas	n.a.			0.99	0.85–1.17	5	11.72	8.86–15.5	5
Average	0.64	0.51–0.81	8	1.15	0.99–1.34	14	3.95	2.42–6.47	20

References of the meta-analysis are given in the reference list under the heading “References used on the meta-analyses”

‘R’ is the response ratio, ‘95%CI’ is the confidence intervals at P<0.95% for the R to be valid, and ‘n’ is the number of data points. If R and the lower 95%CI are larger than 1, then the response is significantly positive; if R and the upper 95%CI are smaller than 1, then the response is significantly negative

* indicates the analysis based on the fixed model, otherwise random model

** indicates data not available

To provide comparisons with microbial parameters, two measurements of soil fertility were included in this meta-analysis: cation-exchange capacity (CEC) and total soil phosphorus content (TSP). In contrast to forest soils, perennial plantations, pastures and annual cropping caused overall decreases in the CEC, but they were not significant, and no effects were observed by the shift from perennial plantation or pasture to annual cropping (Table 3). Probably because of fertilization, TSP increased significantly due to annual cultivation in areas previously occupied by either forests or pastures (Table 3).

Discussion

Soil microbial biomass and its related parameters, such as the ratio of MB-C to TSOC and the metabolic quotient (qCO_2) are widely accepted indicators of soil quality, particularly when used to compare soils under different agricultural uses (Kaschuk et al., 2010). In this study, we measured changes in MB-C, TSOC, MB-C/TSOC, and qCO_2 when a native forest is converted into different agricultural uses. Our analysis showed that any type of agricultural use affected negatively the MB-C and related parameters. For instance, by considering decreases in the ratios of MB-C and MB-C/TSOC when forest soils are converted to agricultural uses, we could hypothesize that the recovery capacity of the soil biological functions in the biome is likely decreased. Following that, productivity of crops is faded to fail over time due to losses in soil quality.

Our meta-analysis has shown that MB-C in Amazon biome is more negatively affected by annual cropping (R=0.47; CI=0.23–0.96; Table 2) and perennial plantations (R=0.68; CI=0.55–0.84) than by pasture (R=0.91; CI=0.81–1.03), which in fact, was not significant. Decreases in TSOC and MB-C/TSOC of Amazon soils taken by pastures were also not significant. Cerri et al. (2003a) have estimated that the conversion of Amazonian forest to pastures resulted, within a 100-year period, in an increase of 54% in the stock of organic C in the top 30 cm of soil (Cerri et al. 2003a). However, later, in an extensive study that included projections of soil-C stocks in the Brazilian Amazon, Cerri et al. (2007) estimated that, in 2030, total soil-C contents would be 7% lower than in 1990.

The Amazon basin possesses over half of the planet's remaining rainforests and comprises the largest and the world's most species-rich tropical-rainforest biome (Turner 2001; Meirelles 2004). Furthermore, Amazonian forests account for about 10% of the world's terrestrial primary productivity and 10% of the stores of C, and it is of strategic importance in issues of global warming and greenhouse-gas inventory (Melillo et al. 1993; IPCC 2001). Unfortunately, results from our study raise concerns about the agricultural use of Amazonian soils for perennial and especially annual crops, where MB-C may be reduced as much as 53% (R=0.47). In addition, despite lower disturbance in soils under pastures, economic and social returns for the extensive cattle-management enterprises in the Amazon are very low (e.g. Meirelles 2004). Our results thus emphasize that new strategies of exploration of areas already deforested in Amazon should be urgently considered and evaluated.

Agricultural activities in the Atlantic Forest biome resulted in similar effects as in the Amazon biome, with a stronger negative effect due to perennial and annual cropping than pastures. It is likely that tropical pastures in the Atlantic Forest, probably dominated by grasses of C4 metabolism showing higher rates of photosynthesis, greatly increase availability of C to the microbial community (Sparling 1997; Feigl et al. 2008a). However, it is intriguing that areas covered with pastures tended to show higher qCO_2, what might indicate lower efficiency in C utilization by the microorganisms. Our results thus show that the composition and efficiency of C use by soil microbes under pastures differ significantly from those under undisturbed soils in the Atlantic Forest, confirming previous suggestions (Barros et al. 2000). The use of qCO_2 as soil quality indicator is still controversial, and a more accepted view is that increases in qCO_2 relate to a lower efficiency in C metabolism (Hungria et al., 2009; Kaschuk et al., 2010). However, if there has been a disturbance that affects the MB-C to a greater extent than the total C pool (e.g., dessication), then an increase in qCO_2 can simply represent a lower C substrate limitation of the MB-C (e.g. Wardle and Ghani 1995).

The introduction of agricultural uses in the Caatinga biome was characterized by non-significant changes due to perennial plantations and pastures, but with strong significant effects due to annual cropping. A lower decrease of MB-C at Caatinga in relation to other biomes could be attributed to natural selection of microbial communities adapted to stressful conditions (high soil temperature and intermittent periods of drought), such that agricultural disturbances were of relatively small magnitude. Furthermore, at least in some of the studies, MB-C of the Caatinga may have been stimulated by improved soil fertility, resulting from inputs of N and P fertilizers especially under annual cropping. It is well known that microbial biomass responds quickly to improvements in soil fertility (e.g. Martens 1987; Nordgren 1992; Andrade et al. 1995; Minhoni et al. 1996).

With the removal of native vegetation in the Cerrado, MB-C consistently showed very low resistance; introduction of perennial plantation, pasture and annual cropping in the biome decreased MB-C by 24, 39 and 64%, respectively. TSOC also declined substantially, but at a lower rate than the MB-C, indicating higher sensitivity of the microbial community to disturbance. In consequence, significantly decreased response ratios for MB-C/TSOC were verified with the introduction of perennial plantations, annual cropping or pastures in the Cerrado, in addition to significant increases in qCO_2. The MB-C/TSOC ratio may indicate that the soil is losing its capacity to support biological activity and probably biodiversity (Insam and Domsch 1988; Anderson and Domsch 1990; Sparling 1997; Seybold et al. 1999; Alvarenga et al. 1999; Souza et al. 2006). In addition, if qCO_2 is increasing, the genetic composition of microorganisms has changed towards a less-efficient metabolism, or the microbes are encountering conditions adverse for survival (Insam and Domsch 1988; Insam and Haselwandter 1989; Balota et al. 1998; Hungria et al. 2009). Therefore, our meta-analysis shows that the Cerrado is one of the most sensitive biomes to the introduction of agricultural activities.

The Cerrado is a Brazilian designation for a savannah-like vegetation complex. This type of vegetation is the product of acid, low-nutrient soils and the tropical bi-seasonal climate with dry and wet periods of approximately equal duration (Adamoli et al. 1986). The poor fertility of the Cerrado soils constrained agricultural use for centuries, however, mainly from the 1970s, new technologies have allowed its exploitation. Prevailing environmental conditions in the Cerrado favor large-scale agriculture: good climate, topography suitable for mechanization, good physical soil characteristics, availability of basic infrastructure, and the existence of lime and P deposits (Embrapa 1976). Based on land-suitability criteria (Goedert 1989; Ker et al. 1992) and on legal requirements for environmental protection, it is estimated that 127 million hectares of the Cerrado are suitable for grain (rain fed and irrigated), pastures and tropical fruits. Accordingly, land has been gradually brought into production such that today estimates are that about 39.5% of the Cerrado present some type of land use activity (Sano et al. 2008). Unfortunately, the results from our study show that microbial communities in the soils of the Cerrado might have a low resilience to changes caused by agricultural activities. Consequently, soil disturbance in the Cerrado profoundly affects C stocks and microbial parameters. However, after deforestation, no significant effects were observed with changes from perennial plantation or pastures to annual cropping, probably because of inputs of fertilizers, reinforcing that proper agricultural activities and the use of high technology should be stimulated in areas under agricultural use, avoiding the deforestation of new areas.

Despite the few data available for agricultural activities in the Pantanal, our meta-analysis shows that MB-C and TSOC of this biome is highly susceptible to cattle ranching (pastures), and the lower MB-C and TSOC stocks could represent environmental degradation. It should also be mentioned that the preservation of Pantanal is highly relevant for the water stocks in South America.

In this meta-analysis, we have revealed that soil disturbance for various land uses impacted negatively the MB-C in the great majority of the studies, with an emphasis on annual cultivation, causing the strongest effect in all biomes, with an average decrease of 53% of the MB-C with the change from natural forests to annual cropping. In addition, our meta-analysis shows that considering the mean values for the main four biomes, decreases on MB-C follow the order: Cerrado (39%)>Amazon (37%)>Caatinga (30%)>Atlantic Forest (25%). In addition, the Cerrado appeared to have the most fragile soil ecosystem because of lower MB-C/TSOC and higher qCO_2 in comparison to the other biomes. Unfortunately, the Cerrado and the Amazon are the biomes undergoing the strongest pressure to expand the agricultural frontier. Therefore, environmental policies are urgently needed to institute practices that address soil disturbance in the Cerrado and Amazon soils, and also in the Caatinga and Atlantic Forest, before microbial growth and function decrease to critical levels. Our study highlights that the use of microbial parameters may help to infer best land-use strategies to improve agriculture sustainability, and the approach can also be very useful to monitor soil quality in other tropical and subtropical biomes.

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