Comparing the sensitivity of physical, chemical and biological properties to a gradient of induced soil degradation

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Abstract
Soil biological and biochemical properties have been proposed as sensitive indicators of soil degradation. Nevertheless, their potential to predict the deterioration of major soil functions related to physical stability, and water and nutrient storage and fluxes has not been validated under experimental conditions. The sensitivity of 16 biological and biochemical variables was contrasted with other eight of chemical or physical nature in a gradient of soil degradation induced by cycles of one, two, three, or four tillage events, plus a no-till control. Twenty-four variables were analysed in soil samples (0-20 cm) collected 60 d after the last cycle. Out of these, 22 were significantly affected by soil disturbance. Six biological (microbial biomass-C, -N, and -C to N ratio; qMic; FDA and urease), two physical (water stable aggregates and aggregate mean diameter) and one chemical variable (org-P) were highly sensitive to soil disturbance. Soil bulk density, invertase activity, organic C and CEC were only slightly sensitive to tillage, whereas qCO_2 and xylanase were not significantly affected by tillage frequency. Although some biological and biochemical properties were highly responsive to soil degradation, there was no general trend of superiority of these variables over those of chemical and physical natures regarding the sensitivity to soil degradation.

Key Words
Soil quality; microbiological indicators; soil enzymes.

Introduction
The search for indicators that may anticipate soil degradation by unsuitable management practices has been one of the main soil scientists' challenges over the past 20 years. Because of the readiness of response of microorganisms to changes in soil environment, soil biological and biochemical properties have been widely proposed as sensitive indicators of soil degradation. Nevertheless, their predictive potential to indicate degradation of major soil functions related to physical structure stability and water and nutrient storage and fluxes has not been validated under experimentally controlled conditions. Here we compared in a tropical kaolinitic soil the sensitivity of a suite of fundamental physical and chemical soil quality indicators with several biological and biochemical variables across an induced gradient of soil degradation.

Methods
Experimental setting
This work was carried out in the Umbauba Experimental Station (Embrapa Coastal Tablelands, Umbauba, Sergipe State, Brazil) in a Typic Fragiudult. This area had been under fallow for 12 years before the beginning of the experiment. Experimental plots (36 x 12 m) were laid out in a Latin Square design with five treatments defined by the application of zero, two, four, six, or eight tillage events (TE). Each event was composed by two disk plowing alternated with two harrowing operations. Treatments were imposed in two cycles between July and September 2006, and November 2006 and March 2007. Within each cycle, events were applied every 15 to 30 days. Between September 2006 and November 2007, vegetation in the plots was controlled by monthly mowing.

Soil sampling and analyses
Sixty days after the last tillage event, soil samples were collected (0-20 cm depth) and analyzed for the following physical and chemical variables: CEC at pH 7.0 (Embrapa 1997); soil organic matter (ignition method); organic P (Anderson and Ingram 1996); available water between -10 e -1500 kPa (pressure plate; Dane and Hopmans 2002); soil bulk density (7,5 to 12,5 cm depth); saturated hydraulic conductivity (double concentric ring method; Reynolds *et al*. 2002); wet aggregate stability and aggregate mean weight diameter (Nimmo and Perkins 2002). Parallel analyses were performed for the following biological and biochemical properties: activity of soil enzymes associated with the cycles of carbon (β-glicosidase (Eivazi and Tabatabai 1988), cellulase, xylanase and invertase (Schinner and Von Mersi 1990), phenol oxidase (Sinsabaugh *et al*.

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1999)), nitrogen (urease; Kandeler and Gerber 1988), phosphorus (acid phosphatase; Tabatabai 1994) and sulfur (arylsulfatase; Tabatabai 1994); fluorescein diacetate hydrolysis (Schnürer and Rosswall 1982); basal soil respiration (Isermeyer 1995); microbial biomass -C and -N (Vance *et al*. 1987; Joergensen and Brookes 1990); and glomalin content (Wright and Upadhyaya 1998). The variables metabolic quotient (qCO_2), microbial quotient (qMIC) and microbial biomass C to N ratio were calculated from the analytical data.

Data analysis

The sensitivity of the indicators to the induced gradient of soil degradation was accessed by the linear regression of the data for each variable as a function of the number of TE, and by the use of contrasts (t-test) between each TE level and the non-till control. The indicators were ranked in the following classes according to their sensitivity to soil disturbance: “very high”, “high”, “medium”, “low”, “very low” and “non-sensitive”. The class “very high” was assigned to variables that had both a significant slope coefficient ($p<0.05$) in the linear regression and whose values at ≥ 2 TE differed significantly ($P<0.01$) from the non-till control. The criteria for the assignment of a variable to the class “high” were the same as for the class “very high”, except that differences between ≥ 2 TE plots and the non-till control were between 1 and 5% of significance ($0.01 < p < 0.05$). The classes “medium” and “low” were assigned to variables with a significant slope coefficient in the regression analysis and whose values differed from the non-till control at ≥ 4 TE and ≥ 6 TE, respectively. Variables that showed no significant differences between TE plots and the no-till control, but had a significant slope coefficient, were classified as of “very low” sensitivity, whereas those that did not show significant differences regarding any of the two statistical criteria were considered as “non-sensitive”.

Results

Mechanical disturbance applied to the soil in two cycles of plowing and disking operations led to significant changes in 22 out of 24 variables tested as soil quality indicators (Table 1). The only two variables that showed no response to mechanical disturbance were qCO_2 and xylanase activity. According to the criteria of sensitivity to soil mechanical degradation, physical, chemical and biological variables were ascribed to six different classes (Table 1). Seven variables, including four biological (microbial biomass-C and -N, qMIC and microbial biomass C to N ratio), two physical (wet aggregate stability and aggregate mean weight diameter) and one chemical (organic P) were classified as of “high sensitivity” to the induced disturbances. Two biological variables (fluorescein diacetate hydrolysis and urease activity) presented “high” sensitivity, whereas seven other variables of the same nature (β-glucosidase, acid phosphatase, arylsulfatase, basal respiration, phenol oxidase, glomalin content and cellulose activity) and two physical variables (saturated hydraulic conductivity and available water) were classified as of “medium” sensitivity. Three variables, soil bulk density, invertase activity, and organic C, were placed in the “low sensitivity” class, and one, CEC at pH 7.0, in the “very low” class. The great majority of the variables affected by mechanical disturbances presented a significant linear decrease in response to the soil degradation gradient (Table 1). However, increasing values along this gradient were observed for microbial biomass C to N ratio, phenol oxidase activity, and soil bulk density.

Conclusion

This is the first study to contrast, in a gradient of induced soil degradation generated under experimental conditions, the sensitivity of a range of biological and biochemical variables and ones of physical and chemical nature of relevance to soil quality. The application of increasing levels of soil tillage events was an efficient method to generate, under experimental conditions, a gradient of soil degradation. This gradient allowed us to study the response and rank the sensitivity to soil degradation of several soil chemical and physical properties in contrast to others of a biological nature. Our results showed that changes in most biological properties coincided with negative changes in soil chemical and physical properties. Although many biological and biochemical properties were highly sensitive indicators of soil degradation, there was no dominance of these properties over chemical and physical ones.

Table 1. Response and sensitivity class of soil physical (P), chemical (C) and biological (B) properties† to the tillage-induced soil degradation. Soil variables were ranked in descending order of sensitivity.

Class of sensitivity	Type of variable	Soil variable	Number of tillage events (TE)					Linear regression model	R^2
			0	2	4	6	8		
Very high	B	MBC (µg C/g)	227.4	183.4***	152.8***	132.2***	134.9***	Y = -23.6*** TE + 213.4	0.86
Very high	B	MBN (µg N/g)	50.8	34.9***	27.3***	24.1***	23.1***	Y = -6.6*** TE + 45.3	0.81
Very high	B	*q*MIC (%)	0.936	0.788***	0.673***	0.604***	0.611***	Y = -0.080*** TE + 0.88	0.83
Very high	B	MB C:N ratio	4.63	5.35**	5.71***	5.68***	5.99***	Y = -0.30*** TE + 4.86	0.82
Very high	F	Water stable aggregate (%)	67.1	54.4**	48.3***	40.7***	45.0***	Y = -5.78*** TE + 62.7	0.71
Very high	F	Aggregate mean diameter (mm)	1.28	0.93**	0.70***	0.62***	0.63***	Y = -0.16*** TE + 1.15	0.75
Very high	Q	Organic P (µg/g)	95.8	70.7**	68.7**	60.7***	67.3**	Y = -6.7*** TE + 86.0	0.68
High	B	FDA hydrolysis (µg fluorescein/g/h)	98.9	80.7*	70.4***	60.7***	62.4***	Y = -9.30*** TE + 93.2	0.71
High	B	Urease (µg N-NH_4^+ /g/h)	5.99	4.77*	4.45**	4.13***	3.50***	Y = -0.56*** TE + 5.69	0.75
Medium	B	β-Glucosidase (µmol PNP/g^{-}/h)	0.74	0.70	0.52***	0.43***	0.39***	Y = -0.10*** TE + 0.75	0.89
Medium	B	Acid phosphatase (µmol PNP / g/h)	7.05	7.07	5.96**	5.47***	5.41***	Y = -0.49*** TE + 7.17	0.86
Medium	B	Arylsulfatase (µmol PNP / g/h)	1.53	1.23	1.01**	0.69***	0.60***	Y = -0.24*** TE + 1.49	0.84
Medium	F	Hydraulic conductivity (cm /h)	19.04	14.17	4.67**	4.47**	4.05**	Y = -3.97*** TE + 17.2	0.67
Medium	B	Respiration (mg C-CO_2 /kg/d)	8.31	7.90	6.50*	5.60***	4.90***	Y = -1.24*** TE + 11.58	0.79
Medium	B	Laccase (nmol DIC /g^{-}/h)	4.82	4.88	6.29*	6.70**	8.07***	Y = 0.83*** TE + 4.50	0.80
Medium	B	Glomalin (µg eq. BSA/g)	2455	2290	2212*	2070**	1875***	Y = -138*** TE + 2456	0.78
Medium	F	Available water (m^3/m^3)	0.262	0.258	0.228*	0.213**	0.208**	Y = -0.015*** TE + 0.26	0.80
Medium	B	Cellulase (µg glucose /g^{-}/h)	64.9	60.0	56.4*	54.8*	53.3**	Y = -2.85*** TE + 63.6	0.77
Low	F	Bulk density (m m^{-3})	1.67	1.63	1.72	1.79***	1.83***	Y = 0.047*** TE + 1.63	0.74
Low	B	Invertase (µg glucose /g^{-}/h)	45.4	42.3	41.4	35.2**	26.8***	Y = -4.43*** TE + 47.1	0.81
Low	Q	Organic C (mg/g)	25.2	25.4	23.5	22.7*	21.2**	Y = -1.13*** TE + 25.0	0.73
Very low	Q	CEC ($cmol_c/dm^3$)	5.31	5.29	5.15	5.05	4.98	Y = -0.090* TE + 5.33	0.72
Non-sensitive	B	qCO_2 (mg C-CO_2 /mg MBC/d)	0.038	0.044	0.044	0.042	0.037	-	-
Non-sensitive	B	Xylanase (µg glucose/g/h)	35.1	26.6	63.8	53.5	41.3	-	-

***P<0.001; **P<0.01; *P<0.05.

† Values of soil properties were adjusted to account for row and column effects associated with the Latin Square design.

MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; *q*MIC, (MBC*1000/ organic C)*100; FDA, fluorescein diacetate; PNP, *p*-nitrophenol; DIC, dihydroindole–quinone–carboxylate; BSA, bovine serum albumin; *q*CO_2, respiration/MBC.

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