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Full Length Research Paper

An assessment on the effects of different land management systems on soil quality, resistance and resilience in Brazil's semiarid region

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Agroforestry represents an alternative to traditional agricultural systems in semiarid regions, since it effectively provides soil coverage and improves the amount and quality of soil organic matter. The sustainability of agricultural systems can be assessed by evaluating soil quality, resistance and resilience. Therefore, this work evaluated soil quality, resistance and resilience under traditional cropping and agroforestry systems. The study took place at an experimental station in Brazil's semiarid northeast region. Studied land use systems include agrosilvopastoral, silvopastoral and traditional cropping, as well as areas under traditional fallow for six and nine years and unaltered ecosystem. Small trenches were dug randomly to collect soil from three depth increments. Soil Quality (SQ) was assessed using chemical, physical and biological indicators. Based on these indicators, resistance, resilience and soil quality indices were calculated. The index quality of the soil was generated using soil water retention, nutrient supply and biological activity promotion functions. Comparisons of index means indicate that agroforests maintained SQ, while traditional fallow systems resulted in improved SQ up to levels similar to the unaltered ecosystem. Traditional cropping lead to a reduction in SQ, resistance and resilience. Agroforestry systems are sustainable. Fallow can improve soil quality, soil resistance and resilience.

Key words: Agrosilvopastoral, silvopastoral, slash-and-burn agriculture, agricultural sustainability, soil management, conservation.

INTRODUCTION

Soil is one of the essential components of the Earth's biosphere. It sustains life, agricultural productivity and natural ecosystems. In recent years, the concern for soil quality has grown to the extent that its use and intensive

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mobilization may cause a decrease in its ability to maintain a sustainable production (Karlen and Stott, 1994). Since soil quality varies with the soil's chemical, physical and biological properties, changes in soil quality brought about by different management strategies can be assessed by measuring those properties. Indeed, managed soils must be monitored in order to preserve their quality and maintain productivity (Benintende et al., 2008). In the 1990s, discussions on agricultural sustainability and soil ecology introduced the terms resilience and soil resistance (Orwin and Wardle, 2004; Seybold et al., 1999). Since then the magnitude of the decrease in soil quality after a change in land use (resistance) and the recovery rate or elasticity (resilience) have both been used to evaluate agricultural sustainability (Seybold et al., 1999). Indices that measure soil resistance and resilience to compare the stability of different ecosystems were proposed by Orwin and Wardle (2004). These indices can be obtained by evaluating chemical, physical and biological indicators that reflect the quality of the soil. A soil's reaction to external and anthropogenic pressures can be described in terms of its resistance and resilience (Kibblewhite et al., 2008).

In recent decades, large areas of Brazil's semiarid region have been degraded by traditional agricultural practices (Sousa et al., 2012). Studies of such systems describe deleterious changes in soil chemical and physical properties through erosion, a decrease in carbon stocks, the depletion of water reserves and reductions in available soil nutrients, especially nitrogen (N) and phosphorus (P) (Aguiar et al., 2010; Maia et al., 2007; Silva et al., 2011). Agroforestry systems represents an efficient strategy to provide soil coverage and improve soil organic matter levels (Breman and Kessler,1997); through the maintenance and management of organic residues provided by trees, crops and animals (Altieri, 2004). Trees are expected to improve soil fertility and benefit crops and pastures through their capacity for depth rooting, nitrogen fixation in some cases and soil retention (Breman and Kessler, 1997). It is expected that soil quality, resistance and resilience in agroforestry systems are similar to those of unaltered ecosystems. To test this hypothesis, the effects of different land management systems (agrosilvopastoral, silvopastoral, traditional cropping and traditional fallow) on soil quality, resistance and resilience were evaluated. This study is a follow up of an earlier study of these same plots (Maia et al., 2007), allowing the authors to use the changes (or lack thereof) to assess resistance and resilience.

MATERIALS AND METHODS

The study was performed in the experimental areas of Crioula Farm (3° 41' S and 40° 20' W), located in Sobral, State of Ceará in northeastern Brazil, in October 2009. Mean annual temperature is between 26 and 28°C, with a dry season lasting from seven to eight months (June to December) and a rainy season between January and May. The climate is dry equatorial tropical, very hot and semiarid, BSW'h according to Köppen's classification (Maia et al., 2007). Six areas were selected (Table 1), including five agroecosystems and one unaltered ecosystem (CAT): i) agrosilvopastoral (ASP); ii) silvopastoral (SILV); iii) six year fallow following traditional cropping (TRAD6); iv) nine year fallow following traditional cropping (TRAD9); v) traditional cropping (TRAD); and vi) caatinga vegetation (CAT). The area's most commonly encountered soil type is Typic Chromic Orthic Luvisol (Aguiar et al., 2010). Six small pits were randomly dug in each land use type in October 2009, and soil samples were collected from depth increments 0 to 5, 5 to 10 and 10 to 20 cm. Soil quality was evaluated using chemical, physical and biological indicators. Indicators included pH in water (1:2.5), exchangeable calcium (Ca), magnesium (Mg) and potassium (K), available phosphorus (P), potential acidity [hydrogen (H) + aluminum (Al)], sum of bases (SB), cation exchange capacity (CEC), base saturation (V), total soil N (TN), soil moisture (M) by weighing and bulk density (Bd) using an undisturbed soil core by clod method. All indicators were analyzed using methods described by Embrapa (1997).

Total organic C (TOC) was quantified by wet oxidation of organic matter using potassium dichromate and sulphuric acid (Yeomans and Bremner, 1988). Microbial biomass C and N (CMB and NMB, respectively) were determined by the irradiation-extraction method (Islam and Weil, 1998) and ratios of CMB to TOC (CMB TOC^{-1} * 100) and NMB to TN (NMB TN^{-1} * 100) were calculated according to Sparling (1992). The evolution of CO_2 - C over time (soil basal respiration, SBR) was also measured. The metabolic quotient (qCO_2) was then calculated by dividing the daily amount of CO_2 produced by CMB (mg CO_2 mg CMB^{-1} d^{-1}) (Anderson and Domsch, 1978). Based on the measured indicators, index quality of the soil (IQS), resistance and resilience were determined. The IQS was calculated as:

$$IQS = \sum qWi\ (wt)$$

Where *qWi* is the value of the numeric weight attributed to each main function and *wt* is the value of the numeric weight attributed to the quality indicator in the assessed function (Karlen and Stott, 1994).

It was used to determine the effects of management on soil quality (Table 2). The main functions chosen to compose this index were: i) water retention (WR), based on quality indicators Bd and TOC since they are related to soil structure and, consequently, water retention capacity; ii) nutrient supply (NS) according to pH, CEC, TN and TOC since they indicate appropriate conditions for nutrition (pH), are directly related to essential nutrients (CEC and TOC) or that can be limiting (TN), and iii) the promotion of biological activity (PBA), defined by CMB and NMB which are influenced by the soil's C/N ratio that itself signals the decomposition process. Each of these main functions was attributed a numeric weight (*Wi*) according to two criteria: i) the sum of the weight of each function must be equal to one; and ii) the value of the weight must reflect the degree of importance of the function in the functioning of soil; therefore, WR was given a weight of 0.4, NS a weight of 0.2 and PBA a weight of 0.4. Greater weight was given to WR and PBA since they are important for the functioning of soils in semiarid regions, directly in the case of water supply (WR) and indirectly through decomposition and nutrient cycling, which are associated to rapid responses to disturbances facilitated by soil biota (PBA). Additionally, numeric weights were attributed to quality indicators based on their level of importance in the function, and the sum of weights for indicators within a function is one.

Values were normalized on a single scale, between zero and one, using the equation $V = 1\ 1 + [(B-L)/(X-L)]^{2\ S\ (B+X-2L)}$ to generate scoring curves (Glover et al., 2000). In this equation, *v* is the normalized score; *B* is the baseline value for the indicator

Table 1. Description of agroforestry and traditional agroecosystems, and unaltered ecosystem located in Sobral - Ceará, Brazil.

Areas	Cropping system	History
Agrosilvo-pastoral (ASP) (1.6 ha)	Corn (*Zea mays* L.) planted in alleys, separated by rows of leucaena (*Leucaena* sp). During the dry season, leucaena is used as fodder for 20 breeder sheep or goats. During the rainy season, leucaena prunings are incorporated into the soil. At corn planting, all of the manure collected from the corral is applied. Annual inputs of organic matter include tree litter, leucaena and native tree prunings, herbaceous biomass and manure. Annual outputs include harvested grain and straw and part of the leucaena prunings for cattle feeding. Dominant tree families are Boraginaceae and Caesalpinaceae.	At plot establishment vegetation was thinned, with 22% of tree cover conserved. Useful wood was partly removed for domestic use and the rest was sold. The remaining woody material was stacked perpendicular to the predominant slope in the area.
Silvopastoral (SILV) (4.8 ha)	Grazing to maintain a flock of 20 breeder sheep or goats. Inputs of organic matter include: wood and leaves pruned at plot establishment, and annual inputs of tree litter and manure. Pasture constitutes the output of organic matter. Dominant tree families are Boraginaceae and Mimosoideae.	During establishment, natural vegetation was thinned, with 38% of tree cover conserved. Useful wood was partly removed for domestic use and sold. The remaining woody material was stacked perpendicular to the predominant slope in the area.
Traditional (TRAD) (0.8 ha)	Agricultural model used in Brazil's semiarid region which involves shifting cultivation: vegetation is slashed and burned and corn (*Zea mays* L.) and beans (*Vigna unguilata* L. Walp) are cultivated for two consecutive years, followed by fallowing. In 2009, soil samples were collected shortly after slash-and-burn.	During the dry season, crop residues and weeds are used as supplementary feed for 20 breeder sheep.
Traditional under fallow for 6 years (TRAD6) (0.8 ha)	Same as above, with vegetation slashed and burned in 2001, corn and beans cultivated over 2002 and 2003, followed by fallow.	
Traditional under fallow for 9 years (TRAD9) (0.8 ha)	Same as above, vegetation was slashed in 1998, corn and beans were cultivated over 1999 and 2000, and the plot was then left fallow.	
Unaltered ecosystem (CAT) (3.1 ha)	*Caatinga* vegetation unaltered for approximately 50 years, used as reference to compare with other plots.	Trees were cut in 1981 and during extremely dry seasons there was grazing.

Source: Maia et al. (2007).

Table 2. Main functions, weights and indicators used to calculate soil quality indices in agroforestry and traditional agroecosystems, Sobral - Ceará, Brazil.

Function	Weight of function (Wi)	Indicator	Weight of indicator (wt)	Lower threshold (L)*	Upper threshold*	Slope at baseline (S)*
Water retention (WR)	0.40	Bd	0.70	1.0	2.0	-2.6170
		TOC	0.30	0.0	18.0	0.0014
Nutrients supply (NS)	0.20	pH	0.10	4.5	9.5	1.3012
		CEC	0.30	0.0	21.0	0.1159
		TN	0.30	0.0	3000.0	0.0090
		TOC	0.30	0.0	18.0	0.0014
Promotion of biological activity (PBA)	0.40	CMB	0.50	0.0	250.0	0.0109
		NMB	0.50	0.0	75.0	0.0342

Bd: Bulk density, TOC: total soil organic carbon, CEC: cation exchange capacity, TN: total soil N, CMB: C in microbic biomass, NMB: N in microbic biomass. *Source: Glover et al. (2000).

with a score of 0.5, which represents the limit between good and poor soil quality; *L* is the lower threshold for the soil indicator, and this value can be zero; *S* is the slope of the tangent to the curve at the baseline and *x* is the indicator's value. The upper and lower threshold values and of the slope of baseline for each indicator were definite according to Glover et al. (2000). The IQS for CAT was used as a reference for the comparison of the agroecosystems. This index varies between zero and one, where one indicates the soil is of high quality for the evaluated function and zero or a value close to zero indicates limited or low soil quality (Glover et al., 2000). In order to compare the stability of agroecosystems, resistance (RS) and resilience (RL) indices were used as proposed by Orwin and Wardle (2004). For 2009 (t_0), the analysis of RS in agroecosystems used soil of CAT as a control, and the RS index varied between +1 (disturbance did not have an effect – maximum resistance) and -1 (stronger effects – less resistance). The equation to calculate resistance is:

$$RS(t_0) = 1 - 2|D_0| / (C_0 + |D_0|)$$

Where *RS* (t_0) is the resistance index in 2009; D_0 is the difference between the response of indicators in the control soil (C_0), unaltered ecosystem CAT, and the disturbed soil (five agroecosystems - Table 1), at the end of the disturbance (P_0), $D_0 = (C_0 – P_0)$; C_0 is the value of the response of the indicator in the control soil (CAT) and P_0 is the value of the response indicator.

The analysis of resilience made use of results obtained by Maia et al. (2007) in 2002 for the control soil (C_X) because Maia et al. (2007) evaluated the same indicators of soil quality in the systems cited using the same methods of analysis which allowed the results to be considered as representatives of a state of the soil at the beginning of the current disturbance suffered areas and therefore to which it is expected for the soil to recover. Disturbed agroecosystem soil is P_X (the state of the ground in the current evaluation) and the difference between systems over the seven years (2002 to 2009) used to assess resilience is D_X. The index was standardized according to the amount of change initially caused by the disturbance (D_0), which determines the condition to which the system must recover. The resilience index (*RL*) also varies between +1 (complete recovery – maximum resilience) and -1 (slowest recovery rate) (Orwin and Wardle, 2004), what can be calculated for seven years (t_7):

$$RL(t_7) = (2|D_0| / (|D_0| + |D_X|)) - 1$$

Data analysis

Soil quality indicators and indices were subjected to an analysis of variance, and means were compared using the Tukey test at a significance level of 0.05. Quality indicators were then separated into explanatory variables (pH, exchangeable Ca, Mg, and K, available P, H + Al, TOC, TN, M and Bd) and response variables (CEC, SB, V, CMB, NMB, SBR, CMB TOC^{-1}, NMB TN^{-1}, qCO_2). The pH was defined as a categorical explanatory variable, with an ideal range for crops between 5.5 and 6.5. To observe similarities between the different management systems, these as well as response variables were ordinated, by soil depth, using non-metric multidimentional staggering (NMDS) and the Bray-Curtis index as a measure of dissimilarity. The two-dimensional distortion of the resolution is represented by the S value (stress). The closer S is to zero the better the fit between the original distance of the objects and the obtained configuration. Principal component analysis (PCA) was used to assess similarities and/or differences between management types, and the relationship between IQS, RS and RL indices. Initially, all calculated RS and RL were used in the PCA. However, in order to explain more than 80% of the total variance with the two first principal components (PCs), some indices was selected. Analyses were performed using statistics software packages SAEG (Sistemas para Análises Estatísticas) version 9.1, STATISTICA (Data Analysis Software System) version 7 and R version 2.

RESULTS

Soil quality

Comparisons of the means of soil quality indicators, by soil depth increment (Table 3) indicate that ASP and SILV maintained soil quality, since indicators in these systems show values equal to or greater than those of CAT (Figure 1). The majority of indicators in SILV did not differ from CAT. In SILV, exchangeable K was high and SBR was low in the second depth increment. When SILV is compared to CAT, NMB, NMB TN^{-1} and M were reduced in the 0 to 5 cm increment, CMB was reduced in the second depth increment and exchangeable Ca was reduced in the second and third depth increments. The ASP system has high values for available P, V and CMB TOC^{-1} (third depth increment) and a low potential acidity. However, there was low SB, CEC, NMB, TOC, NMB TN^{-1} and M (surface), Mg, CMB TOC^{-1}, CMB and M (second depth increment), TN (last increment) and an increase in pH (all three increments). These results and the IQS indicate the effects of management in ASP were greater in the second depth increment (subsurface). In general, the fallow periods were sufficient to allow the improvement of soil quality. In TRAD6, the variables were greater (available P in the second depth increment, exchangeable Ca, SB, CEC and NMB in the second and third depth increments and NMB TN^{-1} in the third depth increment) or equal (pH, available P, exchangeable K and Mg, H + Al, V, CMB, TOC, CMB TOC^{-1}, NMB TN^{-1}, M, Bd and IQS) to those under CAT.

Under TRAD9 indicators, pH, available P, exchangeable K and Mg, H + Al, V, NMB, TOC, NMB TN^{-1} and TN displayed values similar to those under CAT. However, indicators exchangeable Ca, SB, CEC, M (all depths), CMB, CMB TOC^{-1} and SBR (second depth increment) and V (second and third depth increment) were lower, while Bd was greater at all depths when compared to CAT. Soil quality under TRAD was reduced due to greater pH and Bd. Furthermore, in depth increment, 5 to 10 cm available P, exchangeable K, Ca and pH were all lower than in the surface depth increment. Low contents of NMB and CMB, NMB TN^{-1}, CMB TOC^{-1} and M (all three layers) also contributed to the lower soil quality under TRAD. The ordination analysis using the NMDS technique showed similarities between CAT and TRAD6, at all soil depth increments (Figure 2). The similarity between ASP and TRAD and between SILV and TRAD9 can be observed in Figure 2A (stress 113.13 10^{-5}), depth increment 0 to 5 cm and in Figure 2B (stress 1.1924 e^{-14}), depth increment 5 to10 cm. Similarities between TRAD9 and ASP and between

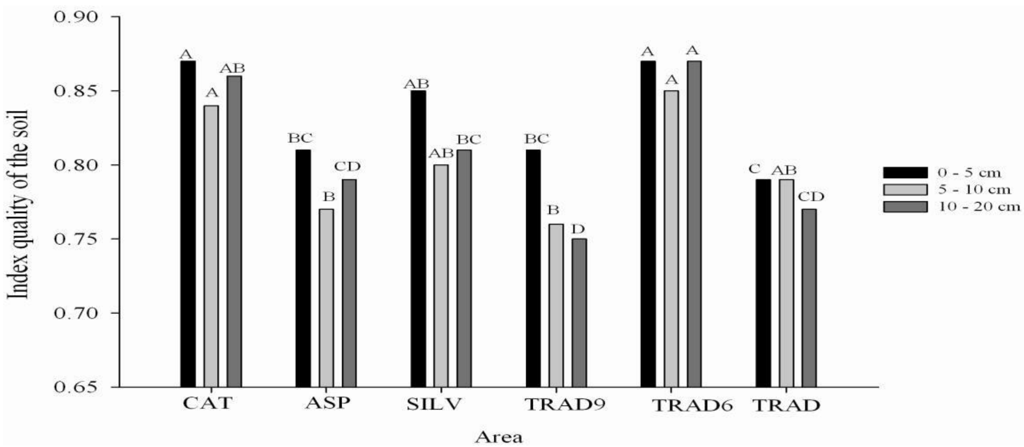

Figure 1. Soil quality indexes for different soil depth increments under agroforestry, traditional cropping and unaltered ecosystem in Sobral - Ceará, Brazil (n = 6). CAT: unaltered ecosystem, ASP: agrosilvopastoral, SILV: silvopastoral, TRAD9: traditional cropping followed by fallow for 9 years, TRAD6: traditional cropping followed by fallow for 6 years, TRAD: traditional cropping. Identical letters above bars indicate that means do not differ at 5% probability according to Tukey's test.

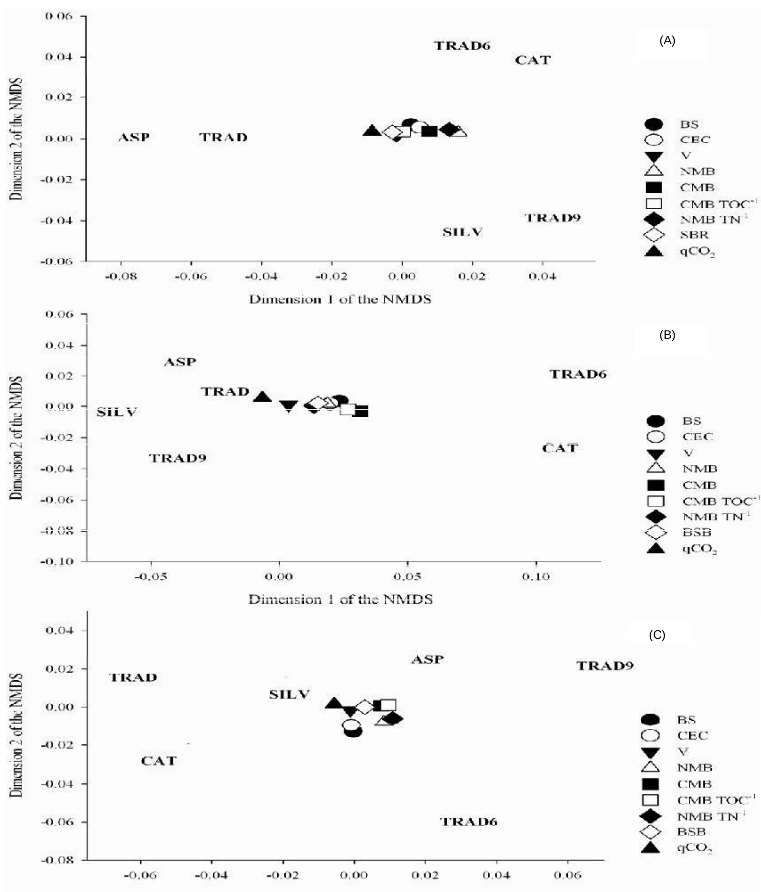

Figure 2. Non-metric multidimensional scaling (NMDS) of soil quality indicators in soil depth increments 0 to 5 cm (A), 5 to 10 cm (B) and 10 to 20 cm (C) at agrosilvopastoral (ASP), silvopastoral (SILV), traditional cropping system (TRAD), traditional cropping followed by fallow for 6 years (TRAD6), traditional cropping followed by fallow for 9 years (TRAD9) and unaltered system (CAT), in Sobral - Ceará, Brazil.

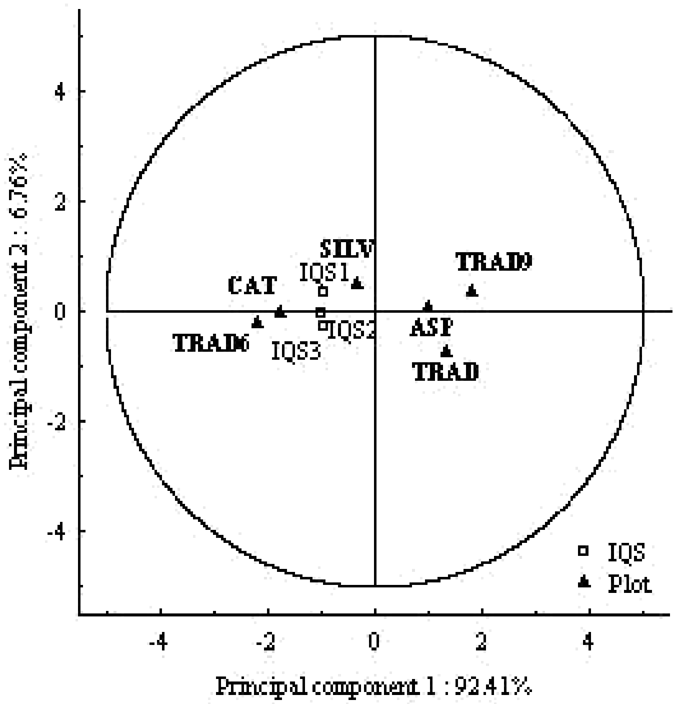

Figure 3. Principal components analysis of plot (▲) and index quality of the soil (IQS, □) for soil depth increments 0 to 5 (IQS1), 5 to 10 (IQS2) and 10 to 20 (IQS3) cm.

Table 4. Soil resistance indices for different soil depth increment and under agroforestry and traditional agroecosystems, Sobral - Ceará, Brazil (n = 6).

Area	pH	P	K	Ca	H + Al	SB	V	CMB	SBR	Bd
0 - 5 cm										
ASP	0.91^{A}	-0.65^{NS}	0.72^{A}	0.57^{NS}	0.27^{B}	0.56^{AB}	0.89^{NS}	0.41^{NS}	0.71^{NS}	0.85^{ABC}
SILV	0.94^{A}	0.44^{NS}	0.34^{B}	0.61^{NS}	0.66^{A}	0.68^{AB}	0.89^{NS}	0.62^{NS}	0.59^{NS}	0.89^{AB}
TRAD9	0.93^{A}	0.55^{NS}	0.56^{AB}	0.44^{NS}	0.60^{A}	0.56^{AB}	0.88^{NS}	0.52^{NS}	0.48^{NS}	0.79^{BC}
TRAD6	0.91^{A}	-0.01^{NS}	0.51^{AB}	0.44^{NS}	0.43^{A}	0.48^{B}	0.86^{NS}	0.61^{NS}	0.63^{NS}	0.96^{A}
TRAD	0.79^{B}	-0.30^{NS}	0.41^{B}	0.56^{NS}	0.37^{A}	0.79^{A}	0.90^{NS}	0.53^{NS}	0.50^{NS}	0.76^{C}
5 - 10 cm										
ASP	0.89^{NS}	-0.35^{B}	0.58^{AB}	0.57^{NS}	0.29^{B}	0.53^{AB}	0.91^{NS}	0.24^{B}	0.79^{AB}	0.78^{NS}
SILV	0.93^{NS}	0.54^{A}	0.86^{A}	0.57^{NS}	0.63^{A}	0.59^{AB}	0.86^{NS}	0.30^{B}	0.41^{C}	0.86^{NS}
TRAD9	0.92^{NS}	0.44^{AB}	0.60^{AB}	0.29^{NS}	0.55^{AB}	0.37^{AB}	0.77^{NS}	0.32^{B}	0.50^{BC}	0.69^{NS}
TRAD6	0.91^{NS}	-0.33^{B}	0.49^{B}	0.34^{NS}	0.50^{AB}	0.30^{B}	0.85^{NS}	0.65^{A}	0.81^{A}	0.88^{NS}
TRAD	0.89^{NS}	-0.07^{AB}	0.54^{AB}	0.47^{NS}	0.62^{A}	0.65^{A}	0.92^{NS}	0.27^{B}	0.68^{ABC}	0.78^{NS}
10 - 20 cm										
ASP	0.89^{NS}	-0.17^{NS}	0.48^{NS}	0.57^{A}	0.37^{NS}	0.55^{A}	0.92^{A}	0.45^{NS}	0.68^{NS}	0.78^{ABC}
SILV	0.92^{NS}	0.50^{NS}	0.74^{NS}	0.46^{AB}	0.55^{NS}	0.56^{A}	0.87^{AB}	0.47^{NS}	0.74^{NS}	0.85^{AB}
TRAD9	0.88^{NS}	0.45^{NS}	0.56^{NS}	0.22^{B}	0.37^{NS}	0.31^{A}	0.69^{B}	0.59^{NS}	0.61^{NS}	0.59^{C}
TRAD6	0.90^{NS}	-0.04^{NS}	0.49^{NS}	0.33^{AB}	0.49^{NS}	0.22^{B}	0.85^{AB}	0.66^{NS}	0.56^{NS}	0.92^{A}
TRAD	0.88^{NS}	0.43^{NS}	0.56^{NS}	0.35^{AB}	0.58^{NS}	0.49^{A}	0.90^{A}	0.59^{NS}	0.61^{NS}	0.71^{BC}

ASP: Agrosilvopastoral, SILV: silvopastoral, TRAD9: traditional cropping followed by fallow for 9 years, TRAD6: traditional cropping followed by fallow for 6 years, TRAD: traditional cropping. NS = values in columns do not differ statistically by the F test. Means followed by same letter do not differ among themselves at 5% probability according to Tukey's test.

Table 5. Soil resilience indices for different soil depth increments and under agroforestry and traditional agroecosystems, Sobral - Ceará, Brazil (n = 6).

Area	P	Ca	Mg	H + Al	CEC	CMB	TOC	NMB TN^{-1}
					0 - 5 cm			
ASP	-0.89^{B}	-0.60^{B}	-0.38^{NS}	0.38^{NS}	-0.47^{NS}	-0.65^{NS}	0.38^{NS}	0.31^{AB}
SILV	-0.24^{A}	0.17^{A}	0.10^{NS}	0.02^{NS}	0.02^{NS}	-0.74^{NS}	-0.11^{NS}	0.66^{A}
TRAD9	-0.95^{B}	-0.54^{B}	-0.54^{NS}	-0.18^{NS}	-0.66^{NS}	-0.78^{NS}	-0.01^{NS}	-0.30^{B}
TRAD6	-0.76^{AB}	-0.12^{A}	-0.34^{NS}	-0.02^{NS}	-0.34^{NS}	-0.81^{NS}	-0.23^{NS}	0.25^{AB}
TRAD	-0.21^{A}	-0.76^{B}	-0.45^{NS}	0.19^{NS}	-0.73^{NS}	-0.69^{NS}	0.19^{NS}	0.42^{AB}
					5 - 10 cm			
ASP	-0.97^{B}	-0.660^{B}	-0.18^{B}	0.68^{A}	-0.49^{AB}	-0.21^{A}	0.19^{NS}	-0.08^{NS}
SILV	-0.16^{A}	0.270^{A}	0.33^{A}	0.07^{AB}	0.17^{A}	0.39^{A}	0.00^{NS}	0.09^{NS}
TRAD9	-0.97^{B}	-0.490^{B}	-0.60^{BC}	-0.17^{B}	-0.56^{B}	-0.13^{A}	-0.02^{NS}	-0.10^{NS}
TRAD6	-0.81^{B}	0.0009^{AB}	-0.66^{C}	0.18^{AB}	-0.16^{AB}	-0.26^{A}	-0.09^{NS}	0.20^{NS}
TRAD	-0.44^{AB}	-0.480^{B}	-0.72^{C}	0.12^{AB}	-0.41^{AB}	-0.07^{B}	-0.07^{NS}	0.18^{NS}
					10 - 20 cm			
ASP	-0.98^{NS}	-0.67^{C}	-0.15^{NS}	0.46^{A}	-0.53^{NS}	-0.51^{NS}	0.42^{A}	-0.21^{NS}
SILV	-0.58^{NS}	0.32^{A}	0.08^{NS}	0.04^{AB}	0.21^{NS}	0.15^{NS}	-0.02^{B}	-0.37^{NS}
TRAD9	-0.97^{NS}	-0.46^{BC}	-0.54^{NS}	0.41^{A}	-0.60^{NS}	-0.78^{NS}	-0.20^{A}	0.17^{NS}
TRAD6	-0.86^{NS}	0.01^{AB}	-0.19^{NS}	-0.37^{B}	-0.28^{NS}	-0.82^{NS}	-0.12^{A}	0.11^{NS}
TRAD	-0.60^{NS}	-0.41^{BC}	-0.49^{NS}	-0.24^{B}	-0.52^{NS}	-0.56^{NS}	-0.37^{A}	0.04^{NS}

ASP: Agrosilvopastoral, SILV: silvopastoral, TRAD9: traditional cropping followed by fallow for 9 years, TRAD6: traditional cropping followed by fallow for 6 years, TRAD: traditional cropping. NS = values in columns do not differ statistically by the F test. Means followed by same letter do not differ among themselves at 5% probability according to Tukey's test.

+ Al, CMB and SBR and TRAD9 for indicators P, K, H + Al and SB, and in the third depth increment TRAD6 had high values for Ca, V and Bd while TRAD9 had a high value for SB. Resistance was high in the agroforestry systems, with the exception of ASP in the second depth increment where RS was the lowest for indicators P, H + Al and CMB. In this depth increment, the greatest RS was found under SILV for indicators P, K and H + Al, followed by TRAD for H + Al and SB. In the last depth increment, high RS was found under ASP for indicators Ca, SB, V and Bd and under TRAD for Ca, V and SB. The TRAD management system had low RS only in the first depth increment, indicating that the effects of such management can be concentrated at the surface.

In the first depth increment, RL was greatest under SILV and TRAD6 for indicators P, Ca and NMB TN^{-1} and lowest under TRAD9 for the same indicators. In the second depth increment, SILV showed the greatest RL for indicators P, Ca, Mg, H + Al, CEC and CMB followed by TRAD6 for Ca, H + Al, CEC and CMB, ASP for H + Al, CEC and CMB and TRAD for P, H + Al and CEC while TRAD9 had the lowest RL for factors P, Ca, Mg, H + Al and CEC. In the third depth increment, the most resilient agroecosystems were SILV and TRAD9 for Ca, H + Al and TOC, followed by ASP for H + Al and TOC and TRAD6 for Ca and TOC, while TRAD had low RL for Ca and H + Al. The PCA revealed that the two first factors explain 84.80% of the total variability among management systems (59.76% for factor 1 and 25.04% for factor 2) in the first depth increment (Figure 4A); 82.35% of total variability (56.17% for factor 1 and 26.18% for factor 2) in the second depth increment (Figure 4B) and 81.38% of total variability (52.04% for factor 1 and 29.34% for factor 2) in the third depth increment (Figure 4C). In surface, TRAD9 and SILV formed a group based on their similarity for indicators H + Al, available P, TN, CEC and Mg and TRAD6 differed from other management systems based on TN, CEC, SB, Ca and TOC. In the 5 to 10 cm depth increment, SILV and TRAD grouped based on similarity for SB, TOC, NMB TN^{-1} and NMB.

In the last depth increment, TRAD6 and TRAD9 were similar, as were ASP and TRAD while SILV differed from others based on indicators exchangeable K and Mg, available P, pH and CMB.

DISCUSSION

Soil quality

Soil quality under agroforestry systems was more similar to the unaltered ecosystem than to traditional cropping. Maia et al. (2007) and Silva et al. (2011) obtained similar results in the same plots of Brazil's semiarid northeast, after assessing soil organic matter pools and soil physical

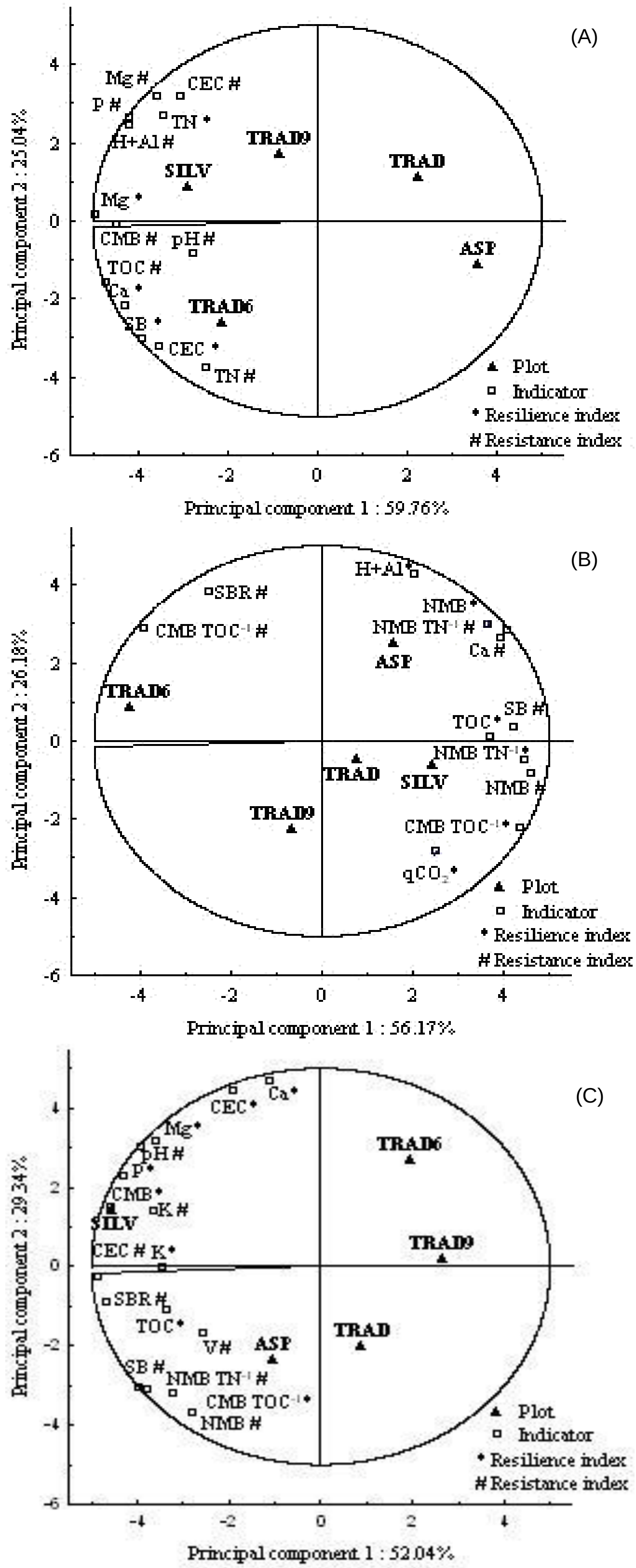

Figure 4. Distribution of indicators (□) according to resistance and resilience indices (#: resistance indices and *: resilience indices), and of plots (▲), for soil depth increments 0 to 5 (A), 5 to 10 (B) and 10 to 20 (C) cm, into PCA correlation circle.

parameters. Such similarities can arise because trees and crops complement each other functionally and structurally (Jordan, 2004), and this favours a constant supply of organic matter to the soil (Maia et al., 2007). The fact that soil bulk density under agroforestry and the unaltered ecosystem was similar must be due to tree roots enabling the formation and stabilization of soil aggregates through physical processes, decomposition and the production of root exudates (Maia et al., 2007). The ASP system likely had the greatest levels of available P because of the application of manure. Indeed, greater V under ASP, as also observed by Maia et al. (2007), confirms the efficiency of this management system in promoting nutrient cycling. The SILV system had the greatest amounts of TOC, as a consequence of the continuous supply of organic residues from diversified root systems, the supply of nutrients in urine and manure and the lack of soil tillage. All of these factors favour the development of the herbaceous stratum and an increase in standing biomass. A rise in TOC under SILV was observed in the mean values of this indicator in the different depth increments, and TOC was 33, 44, 19, 20 and 22% greater under SILV than under TRAD, ASP, CAT, TRAD6 and TRAD9, respectively.

Vegetation cover could have resulted in SILV indicators being higher than under CAT as well as in a high IQS, through better light penetration and the promotion of herbaceous species. Maia et al. (2007) observed 60% herbaceous soil cover under SILV, and only 29% under CAT. The greater organic matter inputs in SILV results in more efficient nutrient cycling (Altieri, 2004), which makes this system appropriate for the production of food and soil conservation (Maia et al., 2007). According to Maia et al. (2007), agroforestry systems ensure a constant supply of organic matter from five distinct sources: tree leaves (1 t ha^{-1} $year^{-1}$), suckers sprouting from stumps and which are incorporated into the soil (2 t ha^{-1} $year^{-1}$), native herbs which are hoed or cut and incorporated to the soil (3 t ha^{-1} $year^{-1}$), aboveground pruning of perennial legumes (2 t ha^{-1} $year^{-1}$) and animal manure (3 t ha^{-1} $year^{-1}$). Thus, in semiarid regions, silvopastoral and agrosilvopastoral models seem to be more appropriate given the association of animal production with either the management of tree vegetation or the management of trees and crops (Maia et al., 2007). Six years of fallow in the traditional system favoured the recovery of soil quality through high chemical and biological fertility as observed in the levels of available P, exchangeable K, Ca and Mg, SB, CEC, V, TOC, NMB and CMB as well as a high IQS. When assessing biological soil indicators, Benintende et al. (2008) observed that three years without tillage yielded more stability in the distribution and growth of microbial communities.

The C and N in microbial biomass and the conversion of TOC and TN into CMB (CMB TOC^{-1}) and NMB (NMB TN^{-1}) reflect the decomposition of organic matter by microbiota (Li et al., 2004). Such decomposition could have occurred in the 5 to 10 and 10 to 20 cm depth increments, given the high values for SB and CEC. Additionally, pH and Bd values under TRAD6 were ideal for plant growth. A nine-year fallow also resulted in improved soil quality; however, the low conversion of TOC into CMB and high respiratory activity in the two uppermost depth increments indicate a slow recovery of microbiota. Indeed, even though microbial biomass was not large, respiratory activity was low and this demonstrates low efficiency in the use of resources. Such low efficiency was also observed by Benintende et al. (2008) in a monoculture, as lower conversion of TOC into CMB. Indeed, the microbial community under TRAD9 is higher than the community under TRAD, which indicates that traditional soil management is detrimental to microbiota and that a long fallow period may be necessary for recolonization. The different responses of the traditional cropping system to fallow can be related to the greater potential acidity found under the 9 years old fallow. Such acidity reduced the amounts of exchangeable K, Ca and Mg, and consequently SB and CEC relative to the traditional system under fallow for six years. Such responses are accentuated by and depend on variations in clay content and mineralogy, which can lead to a reduction in exchange sites and lesser nutrient retention (Maia et al., 2007). Maia et al. (2007) studied the same areas and found greater clay contents under TRAD6, along with greater SB, CEC and V. This increase allowed a more rapid recovery of SQ under fallow for six years than nine years.

In areas where SQ is reduced by slash-and-burn, the fallow period which is necessary to recover SQ can vary according to soil and environmental characteristics such as texture, structure and mineralogy, temperature and water availability. Given that the majority of soil evaluations are made using chemical and some physical properties, it is necessary to reconsider which soil and environmental characteristics are most representative of SQ. Thus, for a more complete soil assessment, we propose the use of soil RS and RL indices. In surface soil under TRAD, residues from slash-and-burn lead to greater soil available P and favoured exchangeable K and Ca, SB, CEC and V. Indeed, values for these indicators lie between those observed under CAT and the other agroecosystems. However, such benefits are short-lived, and the optimal time needed for the recovery of SQ after slash-and-burn is unknown and could be quite long. A reduction in certain elements, a pH above that recommended for crops and low amounts of N and C in microbial biomass, in the second and third depth increments, indicate that benefits from burning are restricted to surface soil.

A reduction in microbiota can compromise environmental services including decomposition and nutrient cycling (Wardle, 1994). According to Alfieri (2004), it is urgent that we conserve and recuperate deteriorated resources in small rural properties. This necessity is justified by signs of environmental degradation in areas sensitive to desertification, by significant losses in biodiversity, by generalized soil erosion and by the siltation and salinization of water sources which is observed after almost four centuries of traditional cropping activities in Brazil's semiarid region (Maia et al., 2007). In the two first depth increments, ASP and TRAD had similar IQS indices and reduced exchangeable Ca, CEC, NMB, and M and greater available P and V when compared to the other areas. This could be due to the periodic slashing of native herbs to reduce competition with crops under ASP, and burning which fractionates the plant cover under TRAD. Also, this similarity can result from the tillage of soil in these management systems. A reduction in TOC under ASP was observed here and by Maia et al. (2007), and can be explained by the oxidation of organic matter due to soil tillage. The similarity in SQ between ASP and TRAD9, in the third depth increment, may result from the greater clay content under ASP as observed by Maia et al. (2007).

More clay leads to better SQ since it provides exchange sites, in addition to the effects of tillage which are observed in surface and subsurface soil.

Soil resistance and resilience

Greater soil RS and RL under agroforestry systems indicate that such management strategies are sustainable. Given that agricultural sustainability is dependent on maintaining levels of or incorporating organic matter into soil (Weiner et al., 2010), ASP and SILV systems are sustainable because abundant amounts of organic matter are added to the soil through the incorporation of the leaf litter, tree root exudates and animal excreta (Altieri, 2004). In the ASP system, the second depth increment was highly resistant and the third increment was highly resilient. The nature and density of plant cover is important in determining the soil's RS and RL since plants can favour elevated levels of biological activity (Seybold et al., 1999). Since the surface soil was disturbed in ASP, the benefits from tree roots could have reduced near the surface. The TRAD6 system showed high RS in terms of Bd in the first depth increment and in terms of CMB and SBR in the second increment. This might indicate that the system is recovering, and surface and subsurface biological communities play an important role in soil RS. These communities mediate important recovery mechanisms such as nutrient cycling, the formation and stabilization of soil aggregates and the control of pathogenic organisms (Seybold et al., 1999). However, RS in terms of CMB and SBR in the same depth increment under TRAD9 was low. This might explain different responses in SQ and stability, and result from the proximity of this plot to the one under TRAD. These two plots were adjacent, and it is possible that a border effect had negative impacts on the TRAD9 plot through a reduction in microbial community, for example. In general, the TRAD system had the lowest RS and RL due to the small amount of live and dead biomass in the field, which results in bare soil and greater nutrient losses and erosion (Weiner et al., 2010). The majority of studies which assessed biodiversity and ecosystem functions found a significant relationship between biological diversity and ecosystem processes (primary productivity, nutrient cycling and trophic interactions). However, in this study, the traditional cropping system, under monoculture, had high RS in the third depth increment. This might be explained by compensatory mechanisms (Proulx et al., 2010). While studying environments with low diversity, Proulx et al. (2010) associated high soil RS to compensatory mechanisms which weaken the relationship between diversity and stability, based on the condition of the soil prior to the disturbance, and not on the absence of any effects of the disturbance. The SILV and TRAD6 systems were generally more resistant and resilient, and as such can maintain soil quality which is key for sustainability (Seybold et al., 1999). On the other hand, TRAD and TRAD9 were less resistant and resilient, likely due to slash-and-burn management in the TRAD plot, since both plots are adjacent.

Additionally, while later studying the same plots, Silva et al. (2011) concluded that the fallow periods were not sufficient for the recovery of soil physical quality, and that subsequent crops affected these properties. It must be kept in mind that, over time, the soil's resistance or capacity to recover its functions after a disturbance can be jeopardized or lost due to inadequate soil management, and this simultaneously results in a reduction in the quality of the soil (Seybold et al., 1999). It follows that traditional cropping which periodically imposes slash-and-burn can be unsustainable, even when the soil is left fallow. Agroforestry systems are sustainable since the soil under them is more resistant and resilient, mainly under silvopastoral management. Traditional soil management leads to reductions in soil quality, resistance and resilience, especially in surface soil. Fallow periods are useful to recover soil quality, resistance and resilience in Brazil's semiarid region.

Abbreviations: CAT, Caatinga vegetation/unaltered ecosystem; **ASP,** agrosilvopastoral; **SILV,** silvopastoral; **TRAD6,** six year fallow following traditional cropping; **TRAD 9,** nine year fallow following traditional cropping; **TRAD,** traditional cropping; **CBM,** microbial biomass C; **NMB,** microbial biomass N; **SBR,** soil basal respiration; **qCO_2,** metabolic quotient; **IQS,** index quality of the soil; **WR,** water retention; **NS,** nutrient supply; **PBA,** promotion of biological activity; **RS,** resistance; **RL,** resilience.

REFERENCES

Aguiar MI, Maia SMF, Xavier FAZ, Mendonça ES, Araújo Filho J, Oliveira TS (2010). Sediment, nutrient and water losses by water erosion under agroforestry systems in the semi-arid region in northeastern Brazil. Agrofor. Syst. 79:277–289.

Anderson JP, Domsch KH (1978). A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biol. Biochem. 10:215-221.

Altieri MA (2004). Linking ecologists and traditional farmers in the search for sustainable agriculture. Front. Ecol. Environ. 2:35-42.

Benintende SM, Benintende MC, Sterren MA, Battista JJ (2008). Soil microbiological indicators of soil quality in four rice rotations systems. Ecol. Indic. 8:704–708.

Breman H, Kessler JJ (1997). The potential benefits of agroforestry in the Sahel and other semi-arid regions. Eur. J. Agron. 7:25–33.

Empresa Brasileira De Pesquisa Agropecuaria (Embrapa) (1997). National Research Center for Land, 2ed Manual methods of soil analysis, Rio de Janeiro, Brazil. (in Portuguese).

Glover JD, Reganold JP, Andrews PK (2000). Systematic method for rating soil quality of conventional, organic and integrated apple orchards in Washington State. Agric. Ecosyst. Environ. 80:29-45.

Islam KR, Weil RR (1998). Microwave irradiation of soil for routine measurement of microbial biomass carbon**.** Biol. Fertil. Soils 27:408-416.

Jordan CF (2004). Organic farming and agroflorestry: alleycropping for mulch production for organic farms of southeastern United States. Agrofor. Syst. 61:79-90.

Karlen DL, Stott DE (1994). A framework for evaluating physical and chemical indicators of soil quality. In: Doran JW, Coleman DC, Bzedicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. Madison, Soil Sci. Soc. Am. (Special Publication, 35):53-72.

Kibblewhite MG, Ritz K, Swift MJ (2008). Soil health in agricultural systems. Philosophical Trans. Royal Soc. B. 363:685–701.

Li FM, Song QH, Jjemba PK, Shi YC (2004). Dynamics of soil microbial biomass C and soil fertility in cropland mulched with plastic film in a semiarid agro-ecosystem. Soil Biol. Biochem. 36:1893-1902.

Maia SM, Xavier FAZ, Oliveira TS, Mendonça ES, Araújo Filho JA (2007). Organic carbon pools in a Luvisol under agroforestry and conventional farming systems in the semi-arid region of Ceará, Brazil. Agrofor. Syst. 71:127-138.

Orwin KH, Wardle DA (2004). New indices for quantifying the resistance and resilience of soil biota to exogenous disturbances. Soil Biol. Biochem. 36:1907–1912.

Proulx R, Wirth C, Voibt W, Weigelt A, Roscher C, Attinger S, Baade J, Barnard RL, Buchmann N, Buscot F, Eisenhauer N, Fischer M, Gleixner G, Halle S, Hildebrandt A, Kowalski E, Kuu A, Lange M, Milcu A, Niklaus PA, Oelmann Y, Rosenkrankz S, Sabais A, Scherber C, Scherer-Lorenzen M, Scheu S, Schulze ED, Schumacher J, Schwichtenberg G, Soussana JF, Temperton VM, Weisser WW, Wilcke W, Schmid B (2010). Diversity promotes temporal stability across levels of ecosystem organization in experimental grasslands. PLoS ONE 10:1-8.

Seybold CA, Herrick JE, Bredja JJ (1999). Soil resilience: Component of soil quality. Soil Sci. 164:224–234.

Silva GL, Lima HV, Campanha MM, Gilkes RJ, Oliveira TS (2011). Soil physical quality of Luvisols under agroforestry, natural vegetation and conventional crop management systems in the Brazilian semi-arid region. Geoderma 168:61–70.

Sousa FP, Ferreira TO, Mendonça ES, Romero RE, Oliveira JGB (2012). Carbon and nitrogen in degraded Brazilian semi-arid soils undergoing desertification. Agric. Ecosyst. Environ. 148:11–21.

Sparling GP (1992). Ratio of CBM to COT as a sensitive indication of changes in soil organic matter. Aust. J. Soil Res. 30:195-207.

Wardle DA (1994). Changes in the microbial biomass and metabolic quotient during leaf litter succession in some New Zealand forest and scrubland ecosystem. Funct. Ecol. 7:346-355.

Weiner J, Andersen SB, Wille WKM, Griepentrog HW, Olsen JM (2010). Evolutionary agroecology: the potential for cooperative, high density, weed-suppressing cereals. Evol. Applic. 3:473-479.

Yeomans JC, Bremner JM (1988). A rapid and precise method for routine determination of organic carbon in soil. Commun. Soil Sci. Plant Anal. 19:1467-1476.