

Glomalin-Related Soil Protein Content in Areas of Degraded and Revegetated Caatinga in the Municipality of Irauçuba

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Abstract

Anthropic activities, combined with the natural ones, may trigger soil degradation, which has increased day by day and contributed to accentuating the desertification processes, resulting in losses of biodiversity and fertility of the soils. Because of that, the utilization of tools that indicate the stages of such degradation and recovery becomes necessary, in order to make viable and adequate management of these areas. Thus, the study on arbuscular mycorrhizal fungi (AMF), as a perspective to facilitate the recovery of degraded areas has increased, especially for the production of glomalin-related soil protein, which is of great importance for aggregate stability, besides showing a great potential of utilization as soil quality indicator. Therefore, the present study aimed to evaluate the contents of glomalin-related soil protein, correlating with chemical, physical and biological attributes in areas of the municipality of Irauçuba-CE: area degraded by overgrazing, area under process of natural revegetation managed with the exclusion of domestic animals and area of native forest, characterized by tree-shrub Caatinga vegetation. Disturbed soil samples were collected in the layer of 0-10 cm in each area and evaluated for AMF attributes, soil chemical attributes and physical attributes. The results obtained with the tests of means prove that, among the three areas, only the native forest showed significant differences with respect to both fractions of the protein. However, in regard to spore density and aggregate stability, the areas of native forest and exclusion showed the best mean values. The content glomalin-related soil protein (GRPS), associated with other edaphic attributes, contributes to discriminating the quality and to the monitoring of areas with different levels of soil degradation. The highest correlation values were observed among the contents of calcium, nitrogen and organic carbon and both GRSP fractions (easily extractable: GRSP_{EE}, which represents the recently deposited fraction that has not yet suffered biochemical alterations in the soil; total: GRSP_T, which is strongly adhered to the clays), indicating that the protein directly influences the contents of these elements in the soil.

Keywords: arbuscular mycorrhizal fungi, degraded area, glycoprotein

1. Introduction

The removal of natural vegetation, combined with long drought periods in the semi-arid regions of Northeast Brazil, lead to physical, chemical and biological modifications in the system, causing a severe increase in soil degradation, compromising the edaphic microbiota and the natural regeneration of the native species (Batista et al., 2009; Silva et al., 2010). The municipality of Irauçuba, located in the Ceará state, has climatic, geological and geomorphological conditions in the soils and vegetation that reflect well the typical characteristics of the semi-arid regions (Sousa, 2009). Extensive livestock farming under overgrazing conditions has caused soil degradation, since it involves the removal of the pre-existing vegetation, increasing the risk of erosion, favoring soil compaction by trampling, reducing porosity, density and, additionally, leading to damages in the water infiltration rate in the soil (Pei et al., 2008).

Studies to make viable the understanding on the physical, chemical and biological aspects of these soils are conducted in such a way to facilitate the comprehension and management of these degraded areas (Sousa et al., 2012a). The studies are conducted in areas under conditions of exclusion of animals, which according to some authors is a management technique that has been considered as a valid tool in the recovery of lands that have not yet been completely degraded (Mekuria et al., 2007; Lipper et al., 2010).

Among the physical, chemical and biological aspects, the biotic components of the soil, especially the arbuscular mycorrhizal fungi (AMF), represent one of the main constituents of the edaphic microbiota that helps in the processes of recovery of the degraded areas, contributing to the aggregation state of eroded soils and thus reducing the risks in the advance of degradation in more-susceptible areas (Schneider et al., 2011). Previous studies emphasize that the importance of the AMF results not only from the mechanical effect of the hyphae, but also from the production of a substance called glomalin, which stands out for constituting an important component of the stock of carbon and nitrogen of the soil and for assisting in the protection of fungal hyphae from desiccation and in the aggregation of mineral and organic particles present in the soil (Barto et al., 2010; Lovelock et al., 2004; Nobre et al., 2015; Peng et al., 2013).

Glomalin, also known as glomalin-related soil protein (GRSP), is a glycoprotein that is hydrophobic, thermostable and recalcitrant, produced by the decomposition of AMF hyphae and spores (Sousa et al., 2012b). Generally, there are two types of GRSP: easily extractable (GRSP_{EE}), which represents the recently deposited fraction that has not yet suffered biochemical alterations in the soil; and total (GRSP_T), which is strongly adhered to the clays (Wright et al., 1996; Wright & Upadhyaya, 1998).

Various studies demonstrate that the GRSP contents have been affected by the changes in land use (López-Merino et al., 2015; Loss et al., 2009; Souza et al., 2010). Considering that the higher the GRSP content, the better the soil quality and that, for exhibiting close correlations with the main soil quality attributes (Purin, 2005; Vaidya et al., 2011), the production of these proteins by the glomalean fungi can be considered as a reinforcement in the indication of soil quality, an aspect still little considered in the evaluation of degradation.

2. Material and Methods

2.1 Location of the Studied Area

The study was carried out in the experimental area of the project “Estudos dos processos de Degradação/Desertificação e suas relações com o uso da terra em Sistemas de Produção no Semiárido cearense: O caso da microrregião de Sobral, Ceará”. The area is located on the Formigueiro Farm in the municipality of Irauçuba (Figure 1) in the Mid-North *Sertão* region of the Ceará state, in the microregion of Sobral, at the coordinates of 03°46'50" S and 39°49'03" W. The municipality has an area of 1,451 km², with altitude of 152.5 m. The climate of the region is semi-arid, with mean annual temperature and rainfall of 26.3 °C and 530 mm, respectively, basically concentrated in three months of the year.

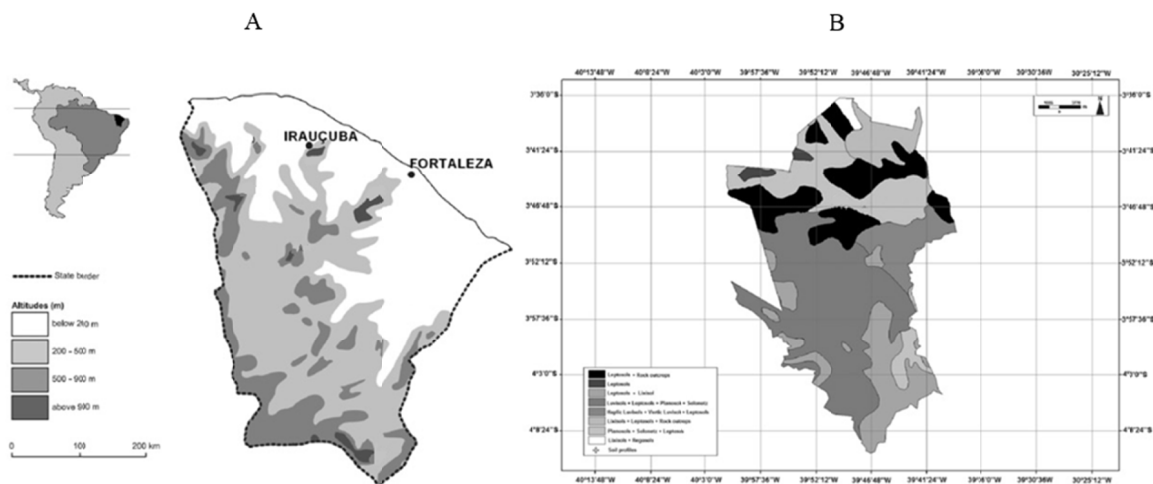


Figure 1. Brazil, Ceará state and the location of the studied area in the rural district of Irauçuba (A), along with the soil survey map of the Irauçuba zone indicating the current associations of soils (B)

2.2 Fieldwork

Soil samples were collected at the end of February 2014, in three areas, all areas with native tree caatinga (mainly black jurema – *Mimosa hostilis*): one area was subjected to exclusion of grazing, which has been fenced for more than 10 years to avoid grazing by cattle, sheep, goats, horses, donkeys, mules and for the evaluation of

natural regeneration processes; another area was subjected to overgrazing, consisting in areas of free access by the animals, used to evaluate the influence of overgrazing over time; and an area under native forest located beside the studied areas and used as a control. Each area has 0.25 hectare and in each one of them 07 soil samples of 1 kilogram each were collected, these samples were manually collected with shovel and conditioned in plastic bags. The samples were collected randomly, passing georeferenced zigzag to a depth of 0-10 cm, and each sample was considered a replication. After collection, the samples were pre-dried in the shade, placed in plastic bags and stored at 10 °C.

2.3 Soil Physical Analyses

The following physical analyses (Table 1) were performed: aggregate stability, through the wet sieving method, whose principle is to measure the amount and distribution of the size of the aggregates that are stable in water, relating them with those that do not disintegrate by sieving; and granulometric analysis, determined through the pipette method (Gee & Bauder, 1986), with dispersion of 20 g of air-dried fine earth (ADFE) using 1 mol L⁻¹ sodium hydroxide. The sands were separated in 0.053-mm-mesh sieves and fractioned according to the reference granulometric classification of the United States Department of Agriculture (USDA). Silt and clay were separated by sedimentation, according to the Stokes' law.

Table 1. Soil physical characteristics: granulometry and aggregate stability in three areas: overgrazing, exclusion and native forest in the municipality of Irauçuba-CE, 2015

Areas/Treatments	Sand (%)	Silt (%)	Clay (%)	AS (%)	Classification
Overgrazing	77.87	10.01	12.12	74.43	Sandy loam
Exclusion	79.00	10.70	10.30	81.91	Sandy loam
Native Forest	68.54	15.14	16.32	85.43	Sandy loam

Note. AS: aggregate stability.

2.4 Soil Chemical Analyses

The chemical analyses of the soil samples (Table 2) were conducted at the Soil-Water-Plant Laboratory of the Soil Sciences Department of the Federal University of Ceará (UFC), namely: pH (in H₂O), measured using a combined electrode immersed in soil suspension; potential acidity (H⁺ Al³⁺), obtained through extraction using buffered solution of calcium acetate at pH 7.0; exchangeable aluminum (Al³⁺), extracted with KCl solution and volumetrically determined with diluted NaOH solution; exchangeable bases (Ca²⁺, Mg²⁺), determined by the KCl method; phosphorus (P-available), determined using an extracting solution (0.05 N HCl and 0.025 N H₂SO₄) and also a diluted acid solution of ammonia molybdate and ascorbic acid powder as reducer, with reading performed through photocolormetry; organic matter (OM) and organic carbon (OC), determined through oxidation of organic matter with potassium dichromate (0.167 N K₂Cr₂) in sulfuric medium (H₂SO₄). The excess of dichromate, after oxidation, was titrated with 0.5 N solution of ammonium iron (II) sulfate [Fe(NH₄)₂(SO)₄·6H₂O] in the presence of diphenylamine indicator with subsequent estimation of the organic matter content. All these methodologies are described by the Manual of Soil and Plant Analysis Methods of EMBRAPA (1997).

Table 2. Mean values of soil chemical attributes in the layer of 0-10 cm in areas of overgrazing, exclusion and native forest in the municipality of Irauçuba-CE, 2015

Chemical attributes	Sampling areas		
	Overgrazing	Exclusion	Native Forest
pH (H ₂ O)	4.96	5.00	5.69
Ca ²⁺ (cmolc kg ⁻¹)	2.37	2.41	6.60
Mg ²⁺ (cmolc kg ⁻¹)	2.07	1.79	3.37
Al ³⁺ (cmolc kg ⁻¹)	0.21	0.37	0.10
H ⁺ Al ³⁺ (cmolc kg ⁻¹)	2.73	4.07	4.77
P (mg kg ⁻¹)	66.18	85.60	18.41
OC (g kg ⁻¹)	4.52	7.39	9.61
N (g kg ⁻¹)	0.64	0.77	1.09
OM (g kg ⁻¹)	7.78	12.70	16.53

2.5 Spore Density

One hundred g of soil were removed from the seven samples of each area for the extraction of AMF spores, following the technique of wet sieving (Gerdermann & Nicolson, 1963). A set of overlapping sieves (with mesh of 850, 250, 100 and 45 μm) was used to extract the total glomerospores. Then, the spores were quantified on a slide with channels using an optical stereoscopic microscope (40 \times).

2.6 Extraction and Quantification of Glomalin-Related Soil Protein (GRSP)

GRSP was extracted through the method proposed by Wright and Upadhyaya (1998), which extracts the following GRSP fractions: easily extractable GRSP - GRSP_{EE}, obtained through the sequential extraction in autoclave, adding 1 g of soil in 8 mL of 20 mM sodium citrate buffer solution (pH 7.0), at temperature of 121 °C for 30 min, and total GRSP - GRSP_T, obtained through sequential extraction using 1 g of soil added to 8 mL of a 50-mM sodium citrate buffer solution (pH 8.0) at 121 °C, for 60 min. Both fractions, after autoclaving, underwent centrifugations at 10000 \times g for 5 min, and the supernatant was removed for later quantification of the protein. GRSP quantification was performed according to the method of Bradford (1976), using the bovine serum albumin protein as standard. GRSP was quantified using an absorbance measurement device (spectrophotometer). The contents of both GRSP fractions were corrected to mg g⁻¹ of soil, considering the total volume of supernatant and the soil dry weight. It is important to note that the Bradford reactive fraction of the GRSP, as reported in this study, does not represent glomalin, that is, the immunoreactive fraction of GRSP. Glomalin is quantified by the monoclonal antibody, MAb32B11 used in the enzyme-linked immunosorbent assay (ELISA) (Rosier et al., 2006). Consequently, the Bradford reactive values in this study probably not represent exactly the content of glomalin; however, there is a direct correlation between the Bradford-reactive and ELISA assays indicating the efficacy of the Bradford assay to provide an estimate of glomalin (Rosier et al., 2006).

2.7 Statistical Analysis

Descriptive statistical analysis was applied to the data through the comparison of means, using the software XLSTAT, free version (XLSTAT, 2014). In addition, data normality at 0.05 probability level was tested using the Shapiro-Wilk test (W) and the mean was tested by the Scott Knott test ($p < 0.01$). Then, the data were analyzed using multivariate statistical tools through the canonical correlation analysis, adopting two sets: Set one (CI), variables related to chemical, physical and biological attributes (pH, Ca²⁺, Mg²⁺, Al³⁺, P, OC, N, AS, SD), and Set two (CII), variables constituted of both GRSP fractions (GRSP_{EE} and GRSP_T). Multivariate analysis was conducted using the software Statistica®, version 7.0.

3. Results and Discussion

3.1 GRSP Fractions in the Three Areas: Overgrazing, Exclusion and Native Forest

The highest mean values of GRSP_{EE} and GRSP_T were found in the native forest area (Table 3). In the areas of overgrazing and exclusion, there was no significant statistical difference between both GRSP fractions. Various authors suggest that the deposition of this protein in the soil mainly occurs by the decomposition of AMF hyphae and spores (Driver, Holben, & Rilling, 2005). Rilling et al. (2003) proved that the GRSP contents are also related to the organic matter in the soil; the higher the contents of organic matter, the higher the GRSP contents. In the present study, the native forest area showed the highest mean values of spore density and organic matter, which possibly explains the highest GRSP contents in this area.

It should be pointed out that the areas of overgrazing and exclusion do not exhibit significant differences regarding the contents of both GRSP fractions (Table 3). However, it is important to highlight that, despite the lack of statistical significance, the area of overgrazing, compared with the area of exclusion, showed the lowest quantitative mean values of the contents of the GRSP fractions. Some authors claim that human activities such as the removal of natural vegetation and inadequate soil use associated with climatic factors, light intensity and temperature, compromise the development of AMF hyphae and spores that are responsible for GRSP production (Mergulhão, 2006; Cardozo, 2011). The studied area of overgrazing has little or no vegetation and a consequent process of degradation, with presence of laminar erosion and inserted in a context of adverse climatic conditions, which may have damaged the production of external mycelium in the soil, the main responsible for the synthesis of GRSP. It is important to remember that the area in question has been degraded by the superpastejo and has undergone the elimination of vegetation by means of anthropic actions for more than twenty years, nevertheless this area presented a reasonable number of spores. Taking into account that AMF are severely affected by degenerative changes imposed on ecosystems, a possible explanation for the number of spores found in the superpastejo area would be the high adaptability of this group of fungi to the adverse conditions of these areas.

Other studies have also shown similar results in relation to the number of spores in degraded areas (Moreira-Souza & Cardoso, 2002; Moreira-Souza et al., 2004; Carrenho et al., 2001).

Table 3. Contents of GRSP_{EE} and GRSP_T (mg g⁻¹ soil) in soil samples of degraded (Overgrazing), managed (Exclusion) and native forest areas in the municipality of Irauçuba-CE, 2015

Areas/Treatments	GRSP _{EE}	GRSP _T
Overgrazing	0.22b	0.18b
Exclusion	0.54b	0.44b
Native forest	0.93a	0.83a

Note. GRSP_{EE} = easily extractable protein; GRSP_T = total protein. Means followed by the same letter in the column do not differ by Scott Knott test ($p < 0.01$).

It is important to note that the area of exclusion, for being under natural regeneration with a greater diversity of plant species and showing higher mean values of spore density and organic matter contents (Tables 2 and 4), in relation to the area of overgrazing, may have contributed to stimulating the occurrence of AMF and, consequently, increasing the deposition of this protein in the soil (Wright & Upadhyaya, 1996).

3.2 Aggregate Stability and Spore Density in the Three Areas: Overgrazing, Exclusion and Native Forest

Comparing the three areas, only exclusion and native forest had almost similar mean values of aggregate stability, and these two areas obtained better percentages of stable aggregates in the soil (Table 4). According to some authors, the stability of soil aggregates is very sensitive to changes in the ecosystems and can be directly altered by the adopted soil management systems (Barto et al., 2010; Sousa, 2009). This fact can be observed in the present study in the area of overgrazing, which showed the lowest mean value of aggregate stability (Table 4), a result that may be attributed to the degradation level of this area.

Bird et al. (2002), comparing the aggregate stability between degraded and non-degraded area in the semi-arid region of New Mexico, USA, found that aggregate stability behaved according to the degradation level, being more stable in areas with greater natural cover, since the organic matter has high influence on soil aggregation.

In regard to spore density in the areas under overgrazing and exclusion, there was no significant statistical difference and these areas obtained the lowest mean values of spores compared with the native forest (Table 4). In the case of these two areas, the one under overgrazing remains under conditions of degradation, because it has little or no natural vegetation and severe presence of laminar erosion, while the area of exclusion, which was thought as a model of recovery of these degraded areas, exhibited very few significant variations in the typical vegetation along these years of fallow (less than 20 years) (Valone & Sauter, 2005; Pei et al., 2008; Zhao et al., 2007). The occurrence of a high number of spores found in the area of overgrazing may be related to the presence of grasses, as well as to the more stressful condition of this environment, causing the AMF to produce a high number of propagules in order to survive, although it is verified that most stresses reduce sporulation (Sylvia & Jarstfer, 1992). Other authors have observed a smaller number of spores in soils with native vegetation in relation to agrosystems with anthropic influence. These authors attribute this pattern to the greater stability of the ecosystem, with more protected surface horizons against sudden disturbances, as well as, a smaller competition for niches, guaranteeing a survival of the species with low sporulation (Caproni et al., 2003).

Table 4. Aggregate stability (AS) and spore density (SD) in soil samples of degraded (Overgrazing), managed (Exclusion) and native forest areas in the municipality of Irauçuba-CE, 2015

Areas/Treatments	AS (%)	SD (100 mL/soil)
Overgrazing	74b	4269b
Exclusion	82a	5031b
Native forest	85a	7833a

Note. AS = aggregate stability; SD = spore density. Means followed by the same letter in the column do not differ by Scott Knott test ($p < 0.01$).

According to McLellan et al. (1995), the propagules of AMF have close link with the processes related to the degradation of the lands that occur in various regions of the world, being severely affected when the soil-plant

interaction suffers the action of environmental imbalance. However, Sylvia and Williams (1992) highlight that a more stressful condition of the environment causes the AFM possibly produces a large number of propagules to survive, a fact not very common, however corroborated with the present study where the native forest had a high number of spores. This is already expected, since these areas are located in the caatinga, which is a unique biome in the world, characterized by the formation of dry forest composed of xerophilous vegetation of arboreal, shrub and herbaceous, with wide variation of physiognomy and flora and high diversity of species, predominating representatives of *Caesalpinaceae*, *Mimosaceae*, *Euphorbiaceae*, *Fabaceae* and *Cactaceae* (Drumond et al., 2000). This caatinga area of the present study is today in accented process of desertification, caused, mainly, by deforestation and inadequate use. It is therefore possible that this stressful environment has induced sporulation as a form of survival and consequently conferred an increase in the number of spores (Franke & Morton, 1994).

3.3 Multivariate Analysis: Canonical Correlations of Chemical, Physical and Biological Attributes with the GRSP Fractions

Table 5 shows the correlations and canonical pairs between physical, chemical and biological attributes related to the contents of both GRSP fractions (GRSP_{EE} and GRSP_T), in three distinct areas (overgrazing, exclusion and native forest) in Irauçuba-CE. For the first pair, the canonical correlations were highly significant (0.01 probability level) by the chi-square test (0.97). Hence, the set CI explains the set CII, in the first canonical pair, thus being of interest for the study. Among the variables related to the contents of both GRSP fractions, the attributes that most contributed to explaining the contents of the GRSP fractions in the soil were Ca²⁺ (R = 0.86), N (R = 0.84), OC (R = 0.84), Mg²⁺ (R = 0.71), pH (R = 0.70) and AS (R = 0.61), respectively. In other words, as the values of CI increased, there is also an increase in the content of GRSP_{EE} (R = 0.94) and GRSP_T (R = 0.99); on the other hand, for the attributes Al³⁺ (R = 0.45), P (R = 0.08) and SD (R = 0.18), there was little or no effect (R < 0.6). For the second canonical pair, there were no significant differences between the attributes of CI and GRSP content (CII) in the soils of Irauçuba-CE.

Calcium (Ca²⁺) was the variable from CI that obtained highest correlation with the variables from CII in the three studied areas (Table 5), thus evidencing in the present study its importance in the production of GRSP. Andrade et al. (1995), studying the coffee crop in Purple Latosol in the Paraná state, observed that the mycorrhizal colonization increased with the addition of limestone. In the present study, Ca²⁺ showed high correlation (0.86) with the contents of both GRSP types, but its highest correlation occurred with GRSP_T. Wu et al. (2014) claim that Ca²⁺ may participate in the establishment of arbuscular mycorrhizae, promoting growth of hyphae and spores that, with the consequent decomposition of these fungal structures, will lead to the formation of GRSP, a fact that may clarify the strong correlation between calcium and the protein produced by glomalean fungi. Nevertheless, such results are controversial and many other authors have demonstrated negative correlation or absence of correlation between this protein and the contents of Ca²⁺ (Lovelock et al., 2004; Mergulhão, 2006).

Table 5. Canonical correlations and canonical pairs between the characteristics of the sets CI (pH, Ca²⁺, Mg²⁺, Al³⁺, P, OC, N, AS and SD) and CII (GRSP_{EE} and GRSP_T) referring to the 21 studied points

Sets	Attributes	Canonical Pairs	
		1	2
		Canonical Correlations	
CI	pH	-0.701	0.078
	Ca ²⁺	-0.864	0.095
	Mg ²⁺	-0.714	0.305
	Al ³⁺	0.456	0.029
	P	-0.082	-0.137
	OC	-0.842	0.063
	N	-0.847	0.053
	AS	-0.618	-0.082
	SD	0.180	0.119
CII	GRSP _{EE}	-0.942	-0.335
	GRSP _T	-0.998	0.055
	R-Canonical	0.973**	0.835 ^{ns}
	Chi-square	55.670	16.094
	DF	20	9

Note. P = phosphorus; Al³⁺ = aluminum; Mg²⁺ = magnesium; Ca²⁺ = calcium; pH = potential of hydrogen; OC = organic carbon; N = nitrogen; AS = aggregate stability; SD = spore density; DF = degrees of freedom; **, *, ns, significant at 0.01, 0.05 probability levels and not significant, respectively. (1) Canonical correlations ≥ 0.6 were considered as significant for comparison purposes.

In decreasing order of correlation, N and organic carbon were the variables that, after Ca²⁺, showed the highest correlations (0.84) with both GRSP fractions (Table 5). However, regarding the two GRSP fractions, GRSP_T showed the highest correlation with the variables N and organic C, which can probably be explained by the fact that this fraction is more stable and, consequently, has a reduced decomposition rate, which leads to higher contents of these two elements in the soil (Rilling et al., 2001; Steinberg & Rilling, 2003).

The positive correlation of the variables N and organic C with both GRSP fractions can be attributed to the fact that this glycoprotein has in its chemical composition considerable amounts of carbon and nitrogen, possibly containing values from 28 to 45% of C and from 0.9 to 7.3% of N, thus constituting a substantial reservoir of C and N in the soils (Rilling et al., 2003; Lovelock et al., 2004; Nichols & Wright, 2006). Organic C is one of the most consistent indicators of GRSP content in the ecosystems (Sousa et al., 2011). Positive correlations between organic C and GRSP have been demonstrated (Bird et al., 2002; Franzluebbers, 2000). Lovelock et al. (2004), working with two soils of Costa Rica, observed that the contents of C and N in the GRSP corresponded to approximately 3.2 and 5% of the total reservoir of C and N of these soils. Similar results were obtained by Rilling et al. (2001).

The pH was another variable from the set CI that showed positive correlation (0.70) with both GRSP fractions of set CII (Table 5). Fungi tend to predominate in acid soils and, since GRSP is produced by AMF, it is expected to find higher production of this protein in acid soils (Haddad & Sarkar, 2003). Possibly, under the condition of acid pH, there is greater preservation of GRSP, because this condition is not favorable to the presence and activity of microorganisms that decompose this protein (Lima et al., 2013). Some authors, however, have observed negative correlation between glomalin contents and soil pH (Rilling et al., 2003; Haddad & Sarkar, 2003; Mergulhão, 2006).

Various studies have demonstrated that GRSP content is highly correlated with soil aggregate stability, consequently promoting improvements in the edaphic structuration and quality, thus contributing to the reduction in the risks of erosion (Wright & Upadhyaya, 1998; Wright & Anderson, 2000; Wright et al., 2007). In the present study, there was a positive correlation (0.61) between both GRSP fractions and aggregate stability (Table 5).

The correlation between GRSP and aggregate stability may be attributed to the recalcitrance and hydrophobicity of this protein, working as an organic ligand, helping in the fixation of particulate material in the soil, besides favoring the formation and improvement in the stability of aggregates (Purin, 2005; Wright et al., 1996). Nobre et al. (2015), studying contents of soil organic carbon and GRSP in different phytophysiognomies in the

Caatinga biome, in the Araripe Plateau (CE), also found positive correlation between the protein produced by the AMF and the stability of soil aggregates.

On the other hand, the variables from set CI, Al^{3+} ($R = 0.45$), SD ($R = 0.18$) and P ($R = 0.08$), showed low correlation with the variables from set CII (GRSP_{EE} and GRSP_T), because the respective variables Al^{3+} , SD and P obtained canonical correlations with values below 0.6 in modulus. According to Santos (2010), variables with values < 0.6 are the ones that least contribute to explaining the correlations between the variables of the formed sets.

4. Conclusions

The contents of the glomalin-related soil protein (GRSP_{EE} and GRSP_T) of the native forest were higher than those found in the areas of exclusion and overgrazing, proving that the intense degradation of these areas contributed to the decrease in GRSP content.

The highest correlations were observed between calcium, nitrogen and organic carbon (Ca^{2+} , N and OC) and both glomalin-related soil protein fractions (GRSP_{EE} and GRSP_T), indicating that these elements of soil influence indirectly the GRSP content of the soil.

The GRSP content, associated with other edaphic attributes, contributes to discriminating the quality and monitoring Caatinga areas with different levels of soil degradation in Irauçuba-CE.

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