Ecological Engineering Using Biological Crusts: Effects on Soil Physicochemical Properties in West-Central region of Burkina Faso

ABSTRACT

The land degradation in Burkina Faso is one of the major development challenges in the agricultural sector. Among the various existing means of soil recovery and improvement, the use of ecological engineering based on soils microorganisms also appears as a tool for sustainable land management. For this purpose, a trial was set up in Péyiri in the West-Center region of Burkina Faso and focused on studying the effects of induced biological crusts on the physicochemical properties of degraded soils. A split-plot design with three replications was set up on three types of soil environment with increasing degradation level, namely "Soil environment with a dense herbaceous layer and some shrubs" (Site 3), "Soil environment with a less dense herbaceous layer" (Site 2) and "Bare soil environment" (Site 1). On each replication plot, three samples core were taken from the 0-20cm layer along the diagonal and were subjected to physicochemical analysis. The organic status (Total C, N and C/N ratio), physical properties (particle size distribution, texture, moisture content), chemical indexes (Séch, CEC, pH, V, Conductivity) and major nutrients (NO_3^-, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Total P) were evaluated. The results obtained revealed that the treatment with the induced biocrust increased the rates of C, N, $S_{éch}$, CEC, V, pH, NH_4^+, P and clay fraction, with much higher moisture. Taking into account the level of soil degradation, the balance on the site 1 presented the highest positive values in N, clay, pF4.5, Sech, CEC, pH, and P. On the site 2 and site 3, the results balance is sometimes positive or negative depending on the considered soil properties. Then the level of soil degradation influenced the biocrust efficiency, but in general the use of induced biocrust led to an improvement in the physicochemical properties of degraded soils especially on some major nutrients such as N and P. Soils in Burkina Faso like the others Sahelian countries are mostly deficient in these major nutrients. The induced biocrusts seem to be as a sustainable management tool for drylands agrosystems.

Keywords: *Land restoration, soil microorganisms, soil quality improvement, Burkina-Faso.*

1. INTRODUCTION

The Sahel is a sensitive and vulnerable area exposed to accelerated loss of natural resources and the related consequence is the increased poverty in rural areas (Ozer et al., 2004). Burkina Faso, such as the others Sahel countries, is an essentially agricultural country (MEDD, 2014). The agricultural sector, which employs nearly 70% of the active population and contributes nearly 35% to GDP (Souratié et al., 2019), is a strategic sector for the development of the country. However, the agricultural sector faces the low productivity of soils as difficulty that limits it development. Among the various causes, climatic factors and inadequate farming practices aggravate the degradation of land fertility. From the assessment of the state of natural resources, land degradation constitutes the main concern for sustainable agricultural production and therefore is a real threat to food security (Ilboudo Nébié E.K. and West, C.T., 2024).

To face this challenge, efforts have focused on land recovery techniques, namely improved short fallows (Tassembedo 2001; Bassanon 2002; Lankoandé, 2022), stone cordons, grassy strips, plowing perpendicular to the slope in order to combat the decline in soil fertility due to loss of the finest elements carried away by water runoff, half-moons and zaï by localized supply of organic matter in basins to retain runoff negative effects. Research on biological crusts has also shown some good effects on soil fertility improvement. Biological crusts can increase soil organic carbon and organic nitrogen through photosynthesis and nitrogen fixation, thus improving soil fertility and keeping soil alive (Gholamhosseinian A., et al., 2021). Additionally, biological crusts can maintain surface stability in different regions (Zhang et al., 2006; Zhao et al., 2010; Li et al., 2022). As the result of their surface morphologies, community composition, and crust development (successional state), biocrust community types vary in their ecosystem function, particularly in regard to soil stability, nitrogen fixation or carbon fixation rates, and dust capture (Williams et al., 2012, Pietrasiak et al., 2013). Felde et al. (2018) explored pedological mechanisms that drive biocrusts' capacity to stabilize soil in the Negev Desert, measuring penetration resistance and cementing agents and their relationships with a suite of soil characteristics. Tiwari, O. N., et al. (2019) has shown that selected microorganisms through ecological engineering can contribute to rehabilitate the soil by inducing the formation of biological soil crusts.

Some authors stressed specifically that biocrusts can cover up to 70% of the soil surface in drylands (Ferrenberg et al., 2015) significantly influencing ecosystem processes such as preventing soil erosion, fixing C and N from the atmosphere, altering soil albedo, regulating water relations, and supporting seed germination and optimal nutrient levels in vascular plants (Concostrina-Zubiri et al., 2017). Studies on biological crusts in Sahel have in fact shown that the presence of cyanobacteria, fungi, lichens and algae which make up the crust, play a very relevant role on the structural stability of the soil, its porosity and on infiltration (Malam et al., 1999). The aim of all these ecological techniques is to enrich and maintain the fine elements (clay, organic matter) in agricultural and forestry environment because the soil fertility is intimately linked to these elements.

Despite these numerous ecosystem services of biocrusts particularly on drylands as in Burkina Faso, there is a lack of information on how induced biocrusts can contribute to enhance soil fertility for the agricultural sector. It therefore seemed interesting to study their effects on physical but also chemical parameters in order to understand the effects on the availability of nutrients. This study aims to evaluate the combined effects of induced biocrusts through ecological engineering on the physicochemical characteristics of degraded soils in West-Central of Burkina Faso.

2. MATERIAL AND METHODS

Description of the study site

Our trial was set up in 2022 on a site of approximately 11ha located in the village of Péyiri in the commune of Koudougou, West-Central region of Burkina Faso. The climate is North Sudanese, hot and dry, characterized by a rainy season from May to September and a dry season from October to April. The average rainfall varies between 600 and 1000 mm per year. The annual evolution of cumulative water levels from 2013 to 2022 shows an average of 821.03 mm of water that has been recorded over the last 10 years. The lowest rainfall was observed in 2013 with a quantity of 608 mm spread over 48 rainy days. The highest rainfall was recorded in 2016 with an amount of 1034 mm spread over 54 rainy days. In addition to the significant variation in rainfall, the stormy and violent nature of the precipitation leads to significant runoff which causes soil erosion. The annual average temperature is 28.1°C. Annual maxima of 39°C are observed from March to May and annual minima of 18°C are between December and January (Météo Burkina, 2023). There are three main types of soil (BUNASOL, 2001):

- Lithosols on cuirasse found at the tops of hills and on gently slopes;
- Hydromorphic soils encountered throughout rivers and lowlands. They are more often sandy-loamy or clayey-sandy associated with ferruginous;
- Leached tropical ferruginous soils, often made up of gravel materials, represent a high proportion, poor in organic matter, nitrogen, phosphorus and potassium with a low exchange capacity.

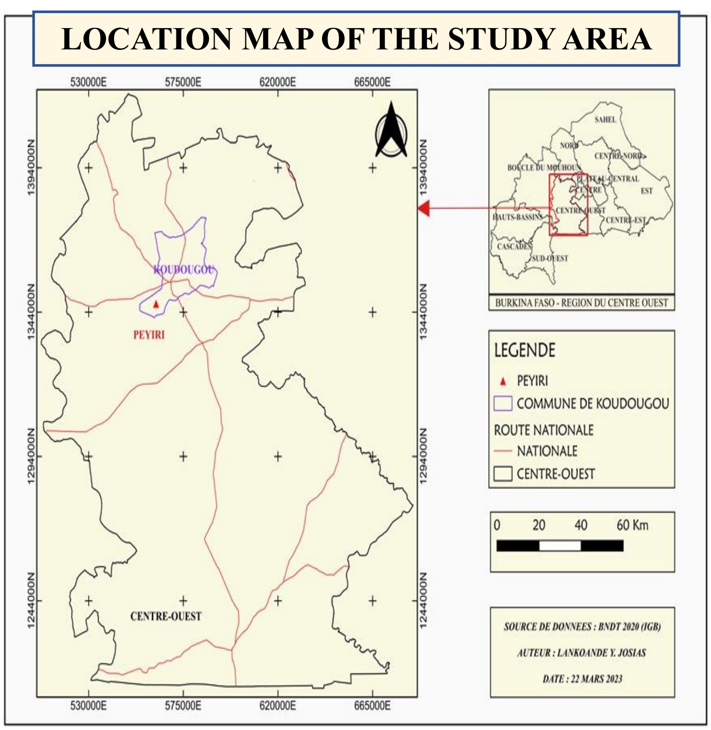

***Fig. 1**: Map of the study area*

Materials

Two types of materials were, namely biological and technical materials. The biological material is the induced biocrust obtained through ecological engineering and the nutrients used to feed the biocrust. The technical equipment is mainly composed of agricultural tools, measuring, mapping and packaging instruments. Pickaxes and shovels were used to open the pits and take soil samples. A GPS was used to take the coordinates of the site. The Qgis software was used to create the map of the study area. Plastic bags were used to package the samples taken. An electronic balance was used to weigh the mass of raw soil before and after sieving and also the mass of biocrust for application. A mortar and pestle were used to break up the clods. A sieve with a mesh size equal to 2 mm was used to sieve the samples.

1,2 = Biocrust used on the plots

3 = Nutrients used to feed the biocrust

Fig. 2: *Some materials used*

Methodology

The methodology followed the different steps summarized in the following workflow:

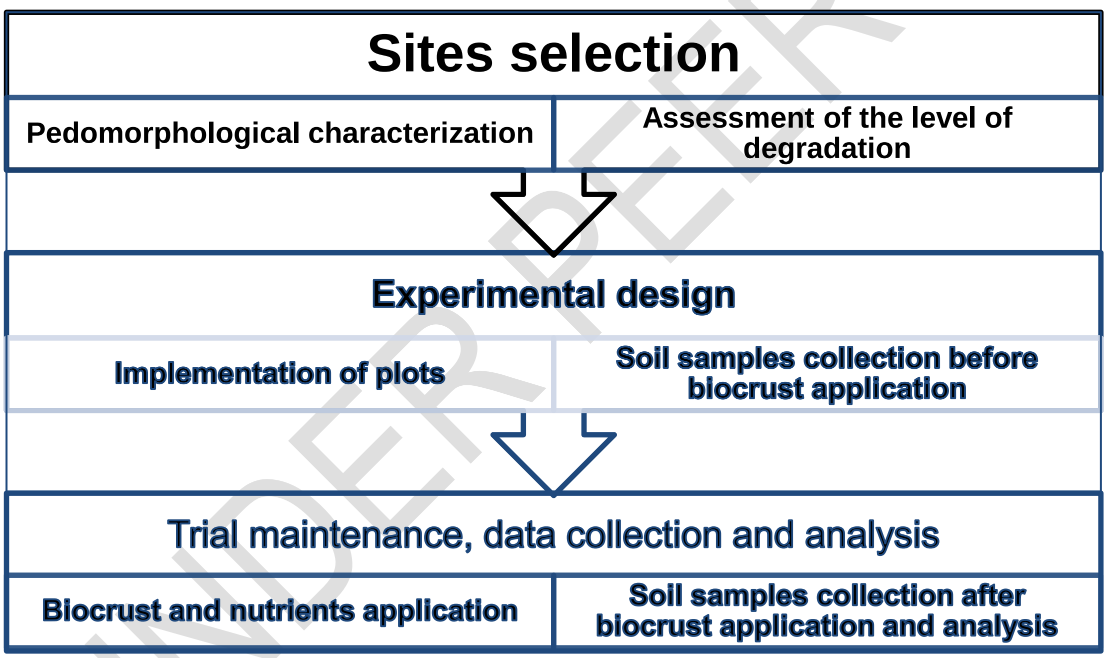

Fig. 3: *Workflow on the different steps*

The first step is the sites selection which is based on the pedomorphological characterization to identify the type of soil and the assessment of the level of soil degradation. After the first step, the experimental design was set up through the plots implementation and then the soil samples collection before biocrust application. Biocrust obtained from selected soil microorganisms have been mixed at different proportion in laboratory and then used on the trial plots at a dose of 100g/m^2. A basal medium was used to maintain the biocrust in activity (Fig 2). The collected soil samples after biocrust application in three replications from 0-20 cm soil layer on each plot, allow to assess the induced effects on the soil physico-chemical properties.

Experimental design

A split-splot design with three repetitions was installed on three types of environments with increasing degradation level, namely “environment with a dense grassy layer and a few shrubs” (Site3), “environment with a less dense grassy layer” (Site2), and “bare environment but immediately surrounded by relatively dense plant formation” (Site1). Two factors were taken into account, the “biocrust” as the main factor and the level of degradation as a secondary one. The estimation gives 80% for site3, 50 to 60% for site2 and 0% for site1.

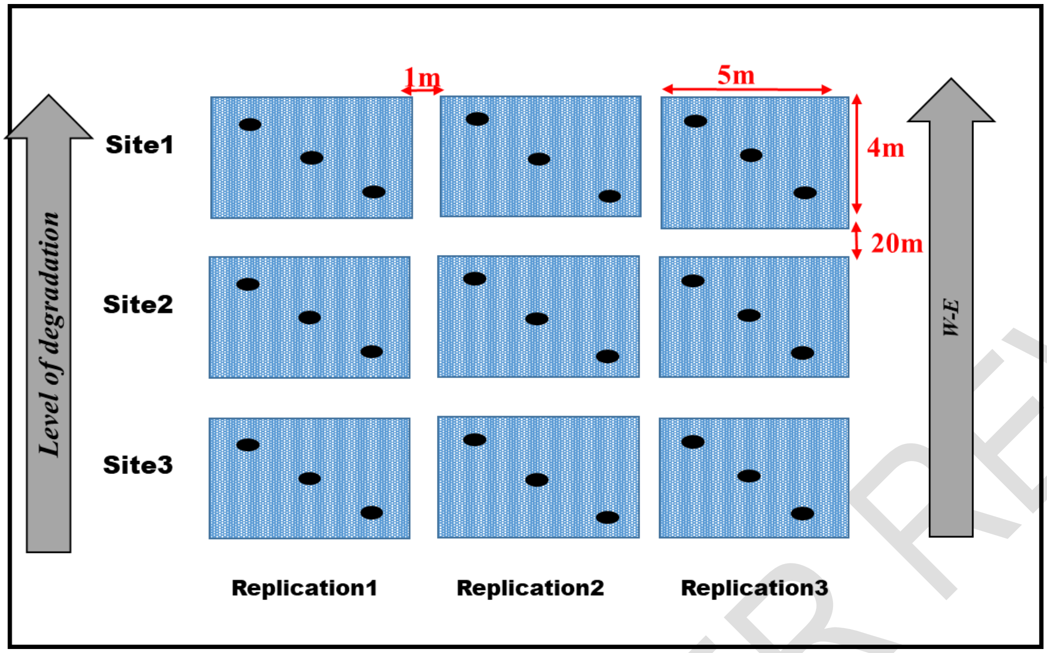

Fig. 4: *Experimental design*

Fig. 5: *Plot treatment with biocrust*

Physco-chemical analysis

A total of 27 samples were collected, packaged in labeled plastic bags and transported to Poznan life sciences University laboratory (Poland). Before the analysis, the samples were air-dried at room temperature and screened through a 2 mm mesh. After this operation, soil pHkcl is potentiometrically measured in the supernatant suspension of a 1:2.5 soil: liquid mixture. The texture was determined by the pipette method after dispersion of the sample with a sodium hexametaphosphate solution (Gee and Bauder 1986). The organic C (Corg) and total nitrogen (N) were determined by dry combustion (Thermo Scientific Lab EA-1110) on carbonate-C free samples. The concentration of soluble elements (Ca, Mg, K, Na etc.) was measured by ICP-OES in a 1:2.5 soil to deionised water suspension, after centrifugation and filtration of the water extracts (Van Reeuwijk, 2002). The exchangeable bases extraction (TEB) was done using the ammonium acetate (pH 7) method and the cation exchangeable capacity (CEC) were determined by ICP-OES after exchange with 0.05 N cobaltihexamine chloride solution (Orsini and Rèmy, 1976, modified by Ciesielski and Sterckeman, 1997). Phosphorus concentration in the obtained extracts was marked with a colorimetric method with blue-staining ammonium molybdate and ascorbic acid and potassium antimonyl tartrate, according to Murphy's and Riley's method. Reading was done on Cary 60 apparatus. The concentration of NO3- and NH4+ ions was measured using the colorimetric method on the Cary 60 apparatus.

Statistical analysis

The data collected were entered using an Excel 2013 spreadsheet. The data were then subjected to an analysis of variance (ANOVA) to compare the means of the variables at the 5% significance level (P<0.05) and the test of Tukey was used for mean separation. The results are presented in table form. The ANOVA was performed using IBM SPSS Statistics software version 22.0.

3. RESULTS AND DISCUSSION

Effects of induced biocrust on the organic status (C, N, C/N) of degraded soils

The results obtained after biocrust treatment presented the highest rate of N (0.017%) and the lowest value of C/N (19.71) compared to those obtained before the treatment (respectively 0.013% and 22. 22). The trend in the C rate remained the same after the biocrust treatment (0.33%). The analysis of variance of the results obtained before and after treatment revealed no significant difference whether on N, C or C/N (p>0.05) (Table I). Some microorganisms constituting the induced biocrust (cyanobacteria) have the capacity to fix atmospheric nitrogen and store it in the soil, which would have increased the content of this element. Biocrusts in effect fix nitrogen (N) and they are an important part of restoring soil fertility (Zhao et al., 2010).

Table I: Effects on C, N of degraded soils

Date	N%	C%	C:N
Before	0,013 ± 0,001	0,33 ±0,007	22,22 ±1,298
After	0,017 ± 0,002	0,33 ±0,014	19,71 ±0,833
P-value	0,372	0,989	0,142
Significance	**NS**	**NS**	**NS**

Legend : P-value = Probability of significance at the 5% threshold (Tukey test); NS = Not significant

Effects of induced biocrust on the physical and chemical properties of degraded soils

The results obtained before the biocrust treatment presented the highest percentages of sand (8.34%) and silt (13.17%) compared to the results obtained after the treatment (respectively 8.07%; 10. 5%). The trend on the clay value revealed a predominance of the value obtained after the biomass treatment (38.67%) compared to that obtained before the treatment (32%). The texture varied from sandy-clayey (SA) to clayey-silty (AL). The analysis of variance on the values before and after treatment revealed significant differences on silt (p<0.05), highly significant on clay (p<0.01) and no significant difference on sand (p>0.05) (Table II). These results are similar to those of Cameron and Devaney (1970), Benap and Gardner (1993), Malam et al. (1999) who showed that the network of filamentous cyanobacteria traps sand grains and clay and silt sized particles adhere to the surfaces of the filaments.

Table III: Effects on the texture of degraded soils

Date	Particles size distribution			Texture
	Sand	Silt	Clay	
Before	8,34 ±0,07	13,17^{a} ±0,00	32^{a} ±0,33	SA
After	8,07 ±0,08	10,5^{b} ±0,69	38,67^{b} ±1,62	AL
P-value	0,088	0,025	0,009	
Significance	**NS**	*	**	

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; NS = Not significant; (*) = significant; (**)=highly significant.

The results obtained before treatment presented the highest humidity levels for pF0.0 (48.67%) and pF2.0 (32.63%) and pF3.7 (25.12%) compared to those obtained after treatment (respectively 46.33%; 28.18 and 20.19). On the other hand, for pF4.2 and pF4.5, the results obtained after treatment presented the highest humidity levels (respectively 18.76%; 10.76%) compared to those obtained before treatment (respectively 18.36%). %; 9.18%). Analysis of variance revealed a significant difference on pF4.5 ($p<0.01$) and no significant difference on pF0.0, pF2.0 and pF3.7 and pF4.2 ($p>0.05$). Some authors showed that during wet soil periods, removal of biocrust led to decreased soil moisture, especially in the upper layer (0.03 m), compared to soils covered by biocrust (Sonia et al., 2013).

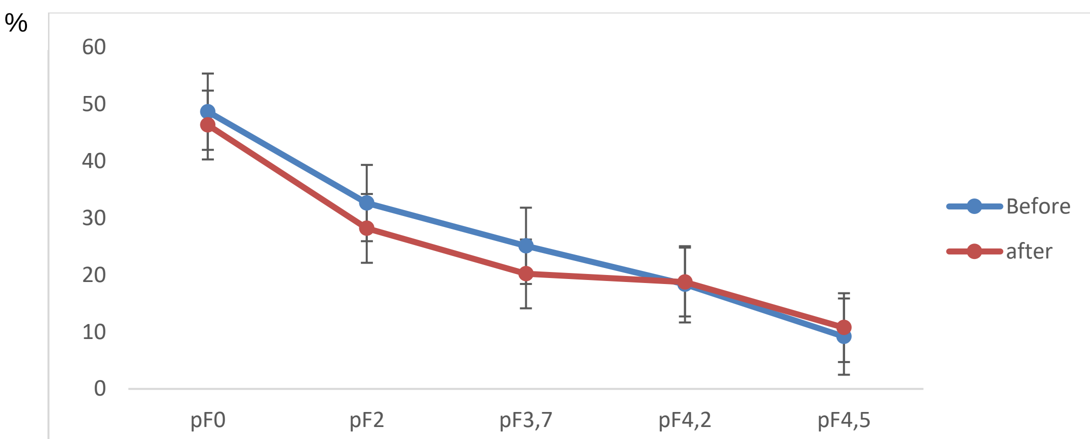

Figure 6: Effects of biocrust on the moisture content of degraded soils

The results obtained after the biocrust treatment presented the highest contents of $S_{éch}$ (4.71 cmol(+)/kg), CEC (6.09 cmol(+)/kg), V (77.02%), and pH (6.75) compared to the results obtained before treatment (respectively 3.95 cmol(+)/kg; 5.42 cmol(+)/kg; 72.67 cmol(+)/kg ; 5.36). The trend in the result obtained in Cdt was higher before treatment (187.2 µS/cm) than after treatment (62.83 µS/cm). The analysis of variance of the results obtained before and after treatment revealed a significant difference on pF ($p<0.05$) and no significant difference on Sec, CEC, V and Cdt ($p>0.05$) (Table III).

Table IIIII: Effects on the chemical indexes of degraded soils

Date	$S_{éch}$_cmol(+)/kg	CEC_cmol(+)/kg	V (%)	pH	Cdt_µS·cm-1
Before	3,95 ±0,43	5,42 ±0,37	72,67 ±2,35	5,36^{a} ±0,13	194,42 ±29,45
After	4,71 ±0,27	6,094 ±0,23	77,02 ±1,81	6,75^{b} ±0,33	187,2 ±24,07
P-value	0,178	0,151	0,272	0,003	0,899
Significance	**NS**	**NS**	**NS**	**	**NS**

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; NS = Not significant; (**)=highly significant ; **Cdt = electric conductivity.**

The results obtained after the biocrust treatment presented the highest contents of NH_4^+ (4.4 mg/l) and P (134.7 mg/kg) compared to the results obtained before treatment (respectively 0.52 mg/l; 115.56mg/kg); 2.79mg/l; 0.52mg/l; 3.03 mg/l) (Table IV). The trend on the content of NO_3^-, K^+, Mg^{2+}, and Ca^{2+} revealed a predominance of the value obtained before biocrust treatment (respectively 107mg/l; 11.36mg/l, 4.48mg/l; 14.58mg/l) compared to that obtained after treatment (respectively 8.66 mg/l; 6.9 mg/l; 2.22 mg/l; 11.93). The analysis of variance of the results obtained before and after treatment revealed a very highly significant difference on NH_4^+ ($p<0.001$) and no significant difference on NO_3^-, P, K, Mg and Ca ($p>0.05$) (Table IV).

Table IV : Effects on the major nutrients of degraded soils

Date	NO_3^-_mg/l	NH_4^+_mg/l	P_mg/kg	K_mg/l	Mg_mg/l	Ca_mg/l
Before	107,56 ±3,57	$0{,}52^{a}$ ±0,37	115,56 ±6,54	11,36 ±0,142	4,48 ±0,65	14,58 ±4,38
After	8,66 ±32,16	$4{,}40^{b}$ ±0,88	134,70 ±5,34	6,9 ±1,27	2,217 ±0,64	11,93 ±2,21
P-value	0,131	0,000	0,055	0,065	0,059	0,607
Significance	**NS**	***	**NS**	**NS**	**NS**	**NS**

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; NS = Not significant; (***)=very highly significant.

Effects of biocrust on the physical and chemical characteristics of degraded soils depending on the level of site degradation

The evolution of the percentages of N and C before and after biocrust treatment revealed an increased value for site1 (respectively 0.004% and 0.0003%), site3 (respectively 0.003% and 0.033%), but a decreased value in percentages for site2 (respectively -0.003% and -0.167%). Site1 presented the highest percentages of N compared to site2 and site3. The more important value of carbon (C) has been obtained on site3. The results on the C/N ratio were negative on all sites. Analysis of variance revealed a significant difference on C ($p<0.01$) and no significant difference on N and C/N ($p>0.05$) (Table V)

Table V : Effects on C, N depending on the level of site degradation

Sites	N%	C%	C/N
Site1	0,0037 ± 0,0024	$0{,}0003^{ab}$ ±0,0237	-2,51 ±1,587
Site2	-0,003 ± 0,0092	$-0{,}1673^{a}$ ±0,0575	-6,894 ±1,909
Site3	0,0033 ± 0,0013	$0{,}0327^{b}$ ±0,0273	-1,526 ±1,044
P-value	0,65	0,023	0,104
Significance	**NS**	*	**NS**

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; NS = Not significant; (*)=significant.

The results on the sand percentage balance revealed a decreased value on site1 (-1.813%) and an increased on site2 (2.65%) and site3 (0.39%). The results on the silt percentage were negative on all sites (respectively -2.67%; -3.72%; -0.50%). On site1 an increased value in the percentage of clay (6.67%) was recorded and a decreased value on site2 (-5.89%) and site3 (-1%). Site2 had the highest percentage of sand and site1 had the highest percentage of clay. The texture varied from sandy-clayey (SL) to clayey-silty (AL) on site1 and remained sandy-silty (SL) on site2 and site3. The analysis of variance revealed significant differences on sand, silt and clay ($p<0.05$) (Table VI).

Table VI: Effects on soil texture depending on the level of site degradation

Sites	Particle size distribution			Texture
	Sable	Limon	Argile	
Site1	-0,27[a] ±0,14	-2,67[a] ±0,76	6,67[b] ±1,02	SA à AL
Site2	2,65[b] ±1,04	-3,72[a] ±0,57	-5,89[a] ±4,33	SL
Site3	0,39[a] ± 0,20	-0,50[b] ±0,42	-1,00[ab] ±0,19	SL
P-value	0,035	0,023	0,036	
Significance	*	*	*	

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; (*) =significant.

For all pF measured (pF0; pF2; pF3.7; pF4.2; pF4.5), the balance was negative on site2 except for pF4.2. It was negative on all sites (site1, site2 and site3) for pF0 (respectively -0.165%; -8.55%; -4.003%) and pF3.7 (respectively -4.94%; -2.81 %; -3.08%). Site1 presented a positive and highest humidity balance for pF4.5 (1.58%), site2 the highest for pF4.2 (2.8%). Analysis of variance revealed no significant differences (p>0.05) (figure 7).

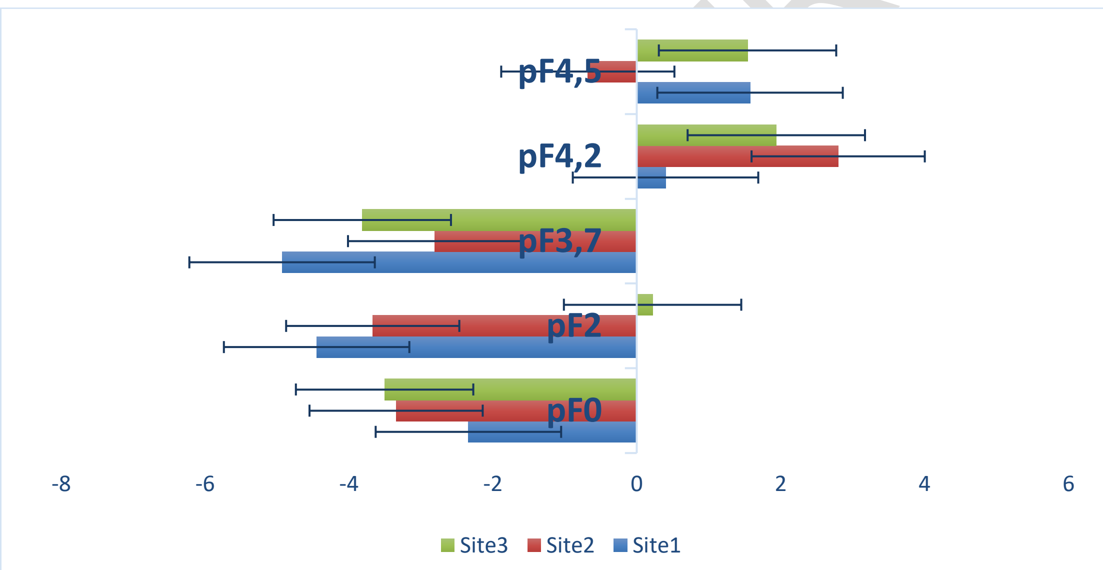

Figure 7: Effects of biocrust on the moisture content

Site1 presented a positive balance on $S_{éch}$ (0.997 cmol(+)/kg), CEC (0.860 cmol(+)/kg) and pH value (1.39) compared to site2 and site3. However, the results were negative and lower on the Cdt (-7.22 µS/cm). Site2 presented a negative balance and the lowest contents of $S_{éch}$ (-0.77 cmol(+)/kg), CEC (-0.96 cmol(+)/kg), V (-2.16%) and positive balance and the highest Cdt content (29.47 µS/cm). Site3 and site1 presented positive results for the V% (respectively 5.75% and 4.35%). The analysis of variance revealed no significant difference in all the parameters measured (p>0.05) (Table VII). The presence of biological soil crusts can significantly change the physical and chemical soil environment (Belnap et al, 2001).

Table VII : Effects on chemical indexes depending on the level of site degradation

Sites	$S_{éch}$_cmol(+)/kg	CEC_cmol(+)/kg	V (%)	pH	Cdt_µS·cm-1
Site1	0,76 ±0,4	0,67 ±0,31	4,35 ±3,14	1,39 ±0,23	-7,22 ±71,30
Site2	-0,77 ±0,47	-0,96 ±0,56	-2,16 ±2,29	1,29 ±0,21	29,47 ±23,98
Site3	0,21 ±0,31	-0,39 ±0,3	5,75 ±7,44	0,78 ±0,21	8,63 ±21,87
P-value	0,086	0,078	0,511	0,181	0,851
Significance	NS	NS	NS	NS	NS

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; NS = Not significant.

The results revealed that site2 presented positive balances and the highest contents of NO_3^- (32.79mg/l), NH_4^+ (8.54mg/l), and K^+ (0.74mg/l) compared to those obtained on site1 (-98.90mg/l; 3.88mg/l; -4.46mg/l) and on site3 (-3.75mg/l; 5.24 mg/l; -2.46 mg/l). Site1 presented the highest P content (19.14mg/kg) compared to the others sites. The balance of Mg^{2+} and Ca^{2+} contents was negative on all sites except for Ca on site3 (1mg/l). The analysis of variance of the results obtained revealed significant differences for P and Mg^{2+} ($p<0.01$), and no significant differences for NO_3^-, NH_4^+, K^+ and Ca^{2+} ($p>0.05$) (Table VIII). Biological soil crusts are known to increase the stability of often easily eroded soils, influence local hydrological cycles in regions that receive limited precipitation, and increase soil fertility (Belnap et al., 2001).

Table VIII : Effects on the major nutrients depending on the level of site degradation

Sites	NO_3^-_mg/l	NH4$^+$_mg/l	P_mg/kg	K^+_mg/l	Mg^{2+}_mg/l	Ca^{2+}_mg/l
Site1	-98,90 ±51,33	3,88 ±0,31	19,14^{b} ±4,92	-4,46 ±1,89	-2,26^{a} ±0,76	-2,65 ± 4,16
Site2	32,79 ±42,81	8,54 ±3,83	3,97^{ab} ±4,96	0,74 ±0,24	-0,42**b** ±0,04	-0,78 ± 0,96
Site3	-3,75 ±1,48	5,24 ±1,67	-1,60a ±3,57	-2,46 ±2,08	-0,32^{b} ±1,00	1,00 ± 0,92
P-value	0,119	0,427	0,042	0,154	0,036	0,617
Significance	NS	NS	*	NS	*	NS

Legend : P-value = Probability of significance at the 5% threshold (Tukey test) ; (*) =significant ; NS = Not significant

4. CONCLUSION

The activities carried out during this study concerned the means of recovering degraded soils and aimed to study the effects of the induced biological soil crust on the physicochemical characteristics of degraded soils in the West-Central region of Burkina Faso. The results revealed that the induced biocrust increased the soil content in organic matter and the levels of physicochemical characteristics of degraded soil. The level of degradation of the environment had an influence on the efficiency of the induced biological soil crusts, increased the levels of chemical characteristics as well as the availability of major nutrients. Biocrusts may reduce land degradation, desertification, and promote sustainable land management, bridging theoretical ecological research with practical applications. It appears important to better understand, by further investigations, the patterns controlling the good functioning of Biocrusts in the Sahel and Savanah regions.

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REFERENCES

Li, M., Liu, Q., Zhang, H., Wells, R.R., Wang, L., Geng, J. Effects of antecedent soil moisture on rill erodibility and critical shear stress. Catena Interdiscip. J. Soil Sci. Hydrol-Geomorphol. Focusing Geoecol. Landsc. Evolut. (2022).
Zhao, Y. et al. Potential nitrogen fixation activity of different aged biological soil crusts from rehabilitated grasslands of the hilly Loess Plateau, China. J. Arid Environ. 74(10), 1186–1191 (2010).
Zhang, Y. M., Wang, H. L., Wang, X. Q., Yang, W. K. & Zhang, D. Y. The microstructure of microbiotic crust and its influence on wind erosion for a sandy soil surface in the Gurbantunggut Desert of Northwestern China. Geoderma 132(3–4), 441–449 (2006).
Williams, A.J., Buck, B.J. & Beyene, M.A. (2012): Biological soil crusts in the Mojave Desert, USA: Micromorphology and pedogenesis. Soil Science Society of America Journal 76: 1685-1695.
Pietrasiak, N., Regus, J.U., Johansen, J.R., Lam, D., Sachs, J.L. & Santiago, L.S. (2013): Biological soil crust community types differ in key ecological functions. Soil Biology and Biochemistry 65: 168-171.
Ferrenberg, S., Reed, S. C. & Belnap, J. Climate change and physical disturbance cause similar community shifts in biological soil crusts. Proc. Natl. Acad. Sci. 112(39), 12116–12121 (2015).
Concostrina-Zubiri, L., Molla, I., Velizarova, E., Branquinho, C. Grazing or not grazing: Implications for ecosystem services provided by biocrusts in mediterranean cork oak woodlands. Land Degradation Develop. (2017).
Y. ZHAO, M. XU, J. Belnap, 2010. Potential nitrogen fixation activity of different aged biological soil crusts from rehabilitated grasslands of the hilly Loess Plateau, China. Journal of Arid Environments Volume 74, Issue 10, Pages 1186-1191
Sonia Chamizo, Yolanda Cantón, Roberto Lázaro , Francisco Domingo, 2013. The role of biological soil crusts in soil moisture dynamics in two semiarid ecosystems with contrasting soil textures. Journal of Hydrology
Volume 489, Pages 74-84
Belnap, J., Prasse, R., Harper, K.T. (2001). Influence of Biological Soil Crusts on Soil Environments and Vascular Plants. In: Belnap, J., Lange, O.L. (eds) Biological Soil Crusts: Structure, Function, and Management. Ecological Studies, vol 150. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-56475-8_21
BUNASOLS, 2001. Morphological study report on soils in the Sissili and Ziro provinces, 83p.

Van Reeuwijk, L.P. (2002) Procedures for Soil Analysis. 6th Edition, International Soil Reference and Information Center, Wageningen.

Bassonon B.S., 2002. Impacts of short natural or improved fallows with Andropogon gayanus Kunth. on the organic, biological and microbiological status of soils in the Sudanian zone of Burkina Faso. Final dissertation Bobo-Dioulasso. Burkina Faso: IDR, Polytechnic University of Bobo-Dioulasso, 58 p.

Belnap J. and Gardner J.S., 1993. Soil microstructure in soils of the Colorado Plateau: the role of the Cyanobacterium Microcoleus vaginatus. Great Basin Nat 53, p40-47.

Cameron, R.E., Devaney, J.R., 1970. Antarctic soil algal crusts: scanning electron and optical microscope study. Trans. Am. Microsc. Soc. 89, p264–273.

Lankoandé Y.J., 2022. Effects of land management methods and microtopography on the physicochemical characteristics of degraded soils in Central West Burkina. Final thesis for the rural development engineering degree, agronomy option. Institute of Environmental Sciences and Rural Development, University of Dédougou, 69p.

Malam Issa O., Trichet J., Defarge C., Coute A., Valentin C., 1999. Morphology and microstructure of microbiotic soil crusts on a tiger bush sequence Niger, Sahel, 23p.

Malam Issa O., Bissonnais L.E., Defarge C., Trichet J., 2001. Role of a microbial cover on structural stability of a sandy soil in Sahelian part of western Niger. Geoderma 101, p15-30.

MEDD, 2014. National Farmers' Day (17th edition, 2014), Introductory document to the sectoral workshop. Ouagadougou, Burkina Faso, 26 p.

Ozer P., Gassani J., Hountondji Y.C., Niang A.J. and Ambouta K., 2004. Is desertification declining in the Sahel?

Souratié W., Koinda F., Decaluwé B. and Samandoulougou R., 2019. Agricultural policies, employment and women's income in Burkina Faso. Development Economics Review. (https//www.cairn.info/revue-d-economie-du-developpement-2019-3-page-101.htm); (visited on August 10, 2023), p101-127.

Tassambedo M.A., 2001. Improving soil fertility under cover with Andropogon gayanus and Andropogon ascinodis: effects on the shortening of the fallow period on a leached ferruginous tropical soil of Sobaka (Sudanian Zone of Burkina Faso). Monitoring of the sptio-temporal structures of plant communities in short-term fallows. Final study dissertation, IDR, Option Eaux et Forêts: Polytechnic University Bobo Dioulasso, 89p.

Williams A.J., Buck B.J. and Beyene M.A., 2012. Biological soil crusts in the Mojave Desert, USA: Micromorphology and pedogenesis. Soil Science Society of America Journal 76, p1685-1695.

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Felde VJMNL, Chamizo S, Felix-Hemmingsen P, Drahorad SL (2018) What stabilizes biological soil crusts in the Negev Desert? Plant Soil. https://doi.org/10.1007/s11104-017-3459-7

Gholamhosseinian, A., Sepehr, A., Asgari Lajayer, B., Delangiz, N., & Astatkie, T. (2021). Biological soil crusts to keep soil alive, rehabilitate degraded soil, and develop soil habitats. Microbial Polymers: Applications and Ecological Perspectives, 289-309.

Tiwari, O. N., Bhunia, B., Mondal, A., Gopikrishna, K., & Indrama, T. (2019). System metabolic engineering of exopolysaccharide-producing cyanobacteria in soil rehabilitation by inducing the formation of biological soil crusts: A review. Journal of Cleaner Production, 211, 70-82.