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# BIOCRUST-BASED LAND RESTORATION: BIOGEOCHEMICAL SIGNATURES FROM AN ERODED SITE IN ICELAND

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## ABSTRACT

Due to climate change and land degradation, the soil has become one of the world's most vulnerable resources. Since the establishment of the Sustainable Development Goals (SDGs) in 2015, land degradation has played a significant part in the United Nations agenda for the environment because land degradation causes decline or loss of land performance. Ecological restoration seeks to enhance recovery of degraded ecosystems, and these restoration activities bring improvement in soil properties. Biocrusts may often develop in reclamation areas following revegetation that involves fertilization. The investigation of soil carbon fluxes and stocks in terrestrial ecosystems, particularly the investigation of soil carbon pool variations under various land uses might offer a foundation for the management of these ecosystems. The main goal of this study was to study measurement methods and some biogeochemical processes of three soil covers in an eroded site in Iceland. Three different soil cover types, biocrust, mixed soil, and bare ground, were identified and measured with a hand-held trace gas analyzer to quantify flux measurements, soil temperature, and moisture over three months. There was no significant difference in $CO_2$ and $CH_4$ flux among the soil covers. However, there was a significant difference in $CO_2$ flux and soil temperature over the study months. There was a significant difference in pH and a weak significant difference in C:N ratio among the three soil cover types with depth. However, no significant difference was observed in mean total nitrogen and soil organic carbon among the soil covers with depth. The study recommends identification of microbes in soil covers that would also improve understanding of the dynamics of these microbes, especially over different times and seasons.



**Keywords:** biocrust, biogeochemistry, $CO_2$ and $CH_4$ fluxes, surface cover, Iceland



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## 1. INTRODUCTION

Due to climate change and land degradation, soil has become one of the world's most vulnerable resources (FAO and ITPS 2015). Since the establishment of the Sustainable Development Goals (SDGs) in 2015, land degradation has played a significant part in the United Nations agenda for the environment because land degradation causes decline or loss of land performance (Akhtar-Schuster 2017). Ecological restoration seeks to enhance recovery of degraded ecosystems (Clewell & Aronson 2006).

Soil conditions have been enhanced through restoration activities that have supplied nutrients to plants (Shimamoto et al. 2018). These restoration activities brought improvement in soil properties (Lal 2015). Several interventions used in Iceland for ecosystem restoration, succession, and function include the use of native species, large-scale seeding of exotic grasses, and fertilization (Arnalds et al. 2013). The outcomes vary. Such interventions are aimed at halting severe erosion and land degradation and promoting sustainable land use.

Biocrust may often develop in reclamation areas following revegetation that involves fertilization. Biocrust occurs in the top few millimeters to centimeters of various soil substrates of desert regions throughout the world (Weber et al. 2016). They include microscopic (cyanobacteria, algae, fungi, and bacteria) and macroscopic (lichens, mosses) poikilohydric organisms (Belnap et al. 2016). According to a recent estimate, biocrusts currently cover 30% of all dryland soils and 12% of the Earth's terrestrial surface (Rodriguez-Caballer et al. 2018; Figure 1).

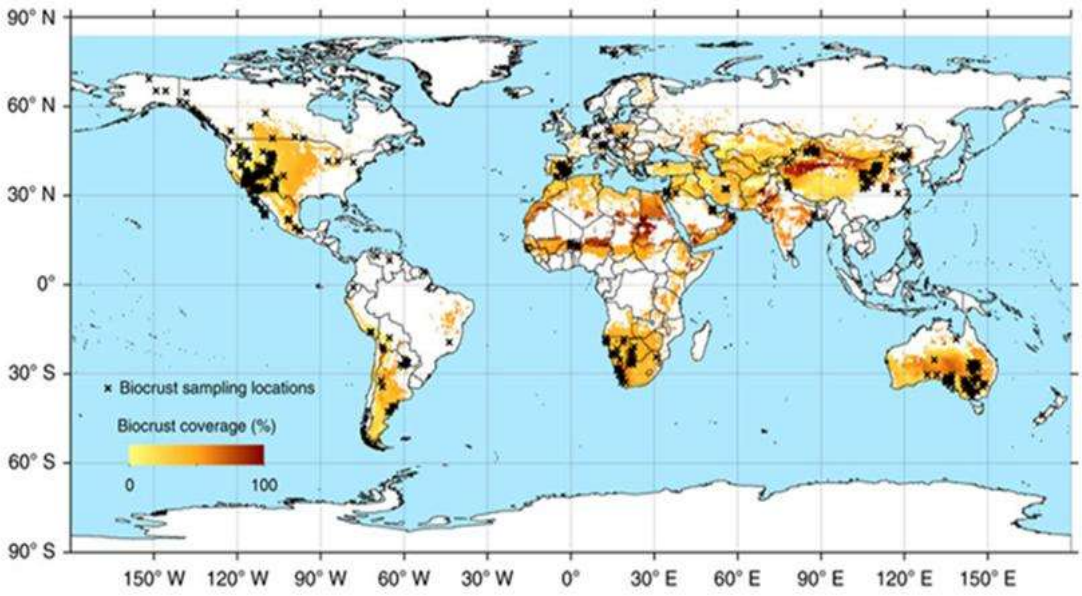


Figure 1. Map showing global biocrust coverage in % within each 0.5°×0.5° pixel. Biocrusts cover a total area of 17.9 million km$^2$, corresponding to 12.2% of the global terrestrial surface. (Source: Rodriguez-Caballero et al. 2018).

Biocrust may account for some biogeochemical processes such as $CO_2$ and $CH_4$ fluxes in desert ecosystems (He 2012). Biocrusts cycle carbon and nitrogen under appropriate environmental conditions (Wang et al. 2022). The investigation of soil carbon fluxes and stocks in terrestrial

ecosystems, particularly the investigation of soil carbon pool variations under various land uses, might offer a foundation for the management of these ecosystems (Wang et al. 2021).

Improving the interaction of soil and vegetation promotes the development of biological soil crusts and influences soil properties (Cao et al. 2008). Climate, soil type, and successional stage all affect the dominant species in the biocrust community (Ferrenberg et al. 2015). The biotic and abiotic parameters that affect biocrust respiration include biocrust cover and composition, air temperature and humidity, soil temperature, and moisture (Miralles et al. 2018). Biocrusts can modify soil temperature (Xiao et al. 2019) and maintain soil stability (Yu et al. 2012).

There have been studies of the influence of biocrust on soil properties (Wang et al. 2022) and, in this study, the contribution of biocrust and their effects on soil properties was also assessed. The study of biocrust in restoration and the ecological services they provide has not been given much attention in Ghana. However, biocrusts have been known to respond to the environment in hot arid or semiarid eco-systems (Rodriguez-Caballero et al. 2018). In view of this, there is a high possibility of biocrust responding to environmental conditions in Ghana. This study in Iceland will offer the opportunity to learn about measurement methods and processes that influence biocrust establishment and enable the potential use of this knowledge in Ghana.

### 1.1 Goal and objectives

The main goal of this study was to study measurement methods and some biogeochemical processes of three soil cover types (bare ground, biocrust, and mixed soil cover) in an eroded site in Iceland.

The specific objectives of the study were:

(i) To estimate the effects of soil temperature and moisture on the various surface covers in March, April, and May 2023

(ii) To estimate carbon dioxide and methane fluxes among the various surface covers in March, April and May 2023

(iii) To establish how carbon dioxide and methane efflux relate to soil temperature and soil moisture

(iv) To determine differences in soil pH and C and N content among soil cover types

## 2. METHODS

### 2.1 Description of site

The study site is in an eroded reclamation area at Borgarfjörður, West Iceland (Figure 2). Gravel surfaces that are sparsely vegetated, including shrubland dominated by Downy Birch (*Betula pubescens*), grassland, and wetlands are typical of the region. According to Arnalds and Oskarsson (2009), the soil in arid regions in Iceland is classified as a Cambic Vitrisol, which has a high concentration of clay and sand and is frequently severely impacted by winter freeze-thaw cycles.




Figure 2: Location of the study site. The road between Borgarnes and Hvanneyri in the North, a gravel mine in the East and Hafnarfjall mountain in the South). (Source: Google Earth).

Some activities have been carried out in the area with the intention to restore the degraded ecosystems in order to reap a variety of advantages, including better grazing land, less wind impact, and enhanced aesthetic appeal. To prevent sheep from grazing there, half of the area has been fenced off, with managed summertime grazing continuing in the other half. In both the grazed and non-grazed areas, restoration practices have been implemented starting in 1999 and including a variety of treatments that are frequently used in restoration work in Iceland (Aradottir et al. 2000). To restore the site's sparse vegetation and enhance its physio-chemical and microbial qualities, fertilization was applied.

## 2.2 Experimental design

Three soil covers were considered: bare ground, biocrust, and mixed soil cover. However, for the purpose of soil analysis, a control that served as a reference with no fertilization was included in the soil sampling. These cover types were visually assessed. The bare ground has no vegetation cover. The biocrust covers are estimated to about 50% or more in the plot and the mixed soil cover contains lichens, algae, and small vascular plants. Three replications were used for each of the covers.

## 2.3 Data collection on fluxes

All flux readings were carried out in hard-plastic rings that had already been installed in the ground. There were nine experimental units, with at least 10 meter distance between units and at least two centimeters for field measurements (Vuojolainen and Uffrecht, 2023, unpublished). The measurements included $CO_2$ flux, $CH_4$ flux, soil temperature (TS), and soil moisture (MS).

A trace gas analyzer, LI-COR 7810 with a Smart Chamber (Soil Gas Flux Survey Chamber), was used to measure $CH_4/CO_2/H_2O$ and soil temperature. A laptop was used for data recording. When the instrument was switched on, it was allowed to warm up, and then the pump protection was taken off. Then, the gas analyzer was connected to the smart chamber. The gas analyzer can be carried on the back of the researcher for convenience and safety purposes. Three sets of measurements were taken at each ring, and if one measurement was notably low or high, a fourth set of measurements was taken. This procedure was completed for all nine rings. These field measurements were taken in May. Data already collected in March and April by other students who are part of the ongoing study were also used in this study. Figure 3 shows the recording of data measurements.



Figure 3: $CO_2$ and $CH_4$ measurements. (Photo: Alejandro Salazar, 25 May 2023).

## 2.4 Soil sampling and soil analysis

Soil samples were collected at depths of 0-5 cm and 5-10 cm. Four samples were taken one meter from each ring. The samples for each depth were bulked and the composite samples kept in sampling bags. The soil samples were transported in ice chests. In the laboratory, soil samples were oven dried at 40°C for 48 hours, sieved through a 2 mm sieve, ball milled and analyzed for C and N content and pH at the soil laboratory at the Agricultural University of Iceland. Soil pH was determined by the Blakemore method and the C and N content was determined with a Vario Max cube from Elementar. The C and N results were reported on a dry matter basis.

## 2.5 Statistical analysis

ANOVA analysis was used to make comparisons between categorical variables and a linear regression approach was used to analyze potential relationships between continuous variables (e.g. between carbon fluxes and soil temperature and moisture). All statistical analyses were conducted in R.

# 3. RESULTS

## 3.1 Gas fluxes, soil temperature and soil moisture

A one-way ANOVA run for $CO_2$ and $CH_4$ fluxes and soil temperature in March between the soil cover types showed no significant difference ($p > 0.05$) as shown in Table 1 and Figure 4. However, the three soil cover types showed high significance ($p<0.001$) with moisture. No results were recorded for the bare ground in March because it was flooded. The biocrust had the highest mean moisture of 0.56 $m^3/m^3$ while the mixed cover had the lowest mean moisture of 0.44 $m^3/m^3$.

For April, a one-way ANOVA run for $CO_2$ between the three soil cover types was weakly significant ($p= 0.057$) as shown in Figure 4. The mixed cover had the highest mean $CO_2$ flux of 0.044 µmol $mol^{-1}$ while the biocrust had the lowest mean $CO_2$ flux of -0.030 µmol $mol^{-1}$. A one-way ANOVA for $CH_4$ flux and soil temperature among the three soil cover types showed no significance ($p>0.05$).

For May, a one-way ANOVA run for $CO_2$ and $CH_4$ fluxes and soil temperature between the soil cover types showed no significance ($p > 0.05$) as shown in Figure 4. However, a one-way ANOVA run for soil moisture between the three soil cover types showed high significance ($p<0.001$). The bare ground had the highest mean moisture of 0.74 $m^3/m^3$. The biocrust had the lowest mean moisture of 0.43 $m^3/m^3$.

There was a significant difference of $CO_2$ flux ($p<0.05$) and soil temperature ($p<0.001$) with months and significant difference of soil moisture with soil cover type ($p<0.05$). However, there was no significant difference in $CH_4$ flux among the soil covers and months.

The results of one-way ANOVA for CO2 and CH4 fluxes, soil temperature, and moisture with regard to the soil cover types and months are shown in Table 1.

**Table 1**: One-way ANOVA results for $CO_2$ and $CH_4$ fluxes, soil temperature, and moisture with regard to soil cover type and month (TS=soil temperature, MS= soil moisture). Shown are F-values and p-vales.

| | $fCO_2$ F-value | $fCO_2$ p-value | $fCH_4$ F-value | $fCH_4$ p-value | TS F-value | TS p-value | MS F-value | MS p-value |
|---|---|---|---|---|---|---|---|---|
| Soil cover | 0.724 | 0.685 | 1.996 | 0.054 | 1.033 | 0.425 | 4.119 | 0.00036 |
| Month | 4.614 | 0.013 | 1.723 | 0.186 | 164.5 | <2e-16 | 1.361 | 0.263 |

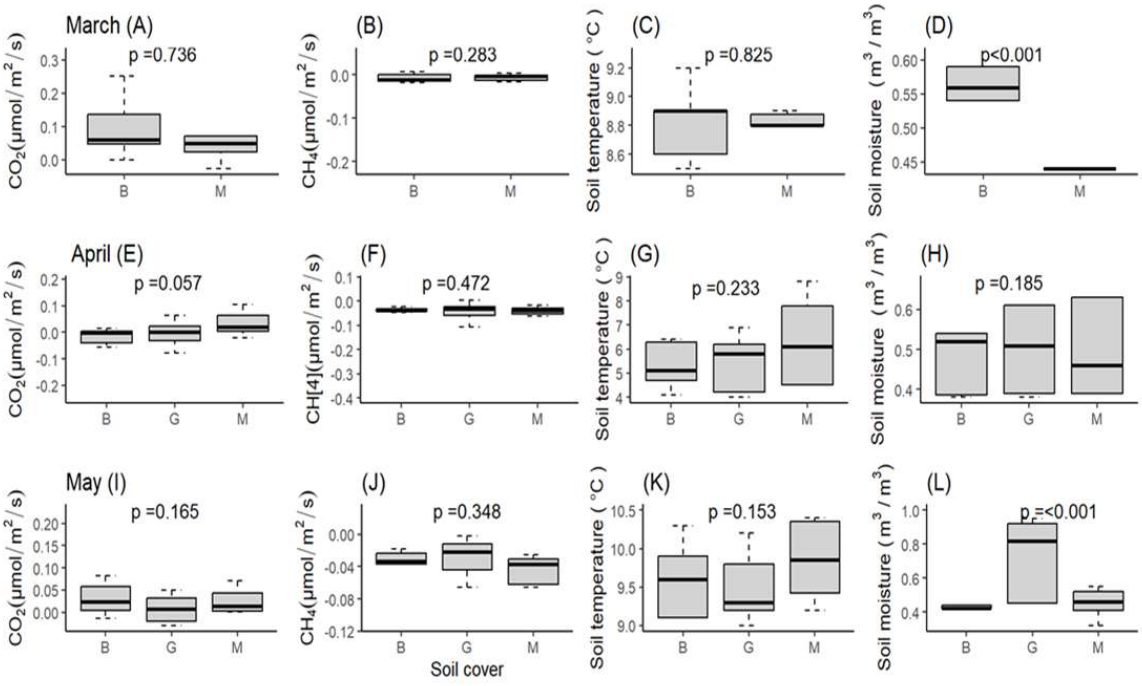


Figure 4: Boxplots showing the distribution of gas fluxes, soil temperature, and moisture among the soil cover types, in March, April and May. B=biocrust, G= bare ground, M=mixed ground.

### *3.1.1 Relationship between fluxes, soil temperature and moisture*

Correlation analysis was used to test relationships between fluxes, soil temperature and moisture (Table 2). There was no significant relationship between $CO_2$ flux and soil moisture. Neither was there any significant relationship between $CH_4$ flux and soil temperature nor between $CH_4$ flux and moisture. However, the was a significant and weak positive relationship between $CO_2$ flux and soil temperature (Fig. 5).

**Table 2**: Linear regression coefficients and their significance: $*p < 0.05$, NS not significant (TS=soil temperature, MS= soil moisture).

| | $fCO_2$ | | $fCH_4$ | |
|---|---|---|---|---|
| Soil cover | R2 | p-value | R2 | p-value |
| MS | 1.264e-05 | 0.971 | 0.010 | 0.384 |
| TS | 0.0735 | 0.020 | 0.012 | 0.341 |
| MS* TS | 0.0797 | 0.657 | 0.023 | 0.580 |
| fCH4 | 0.0095 | 0.406 | - | - |

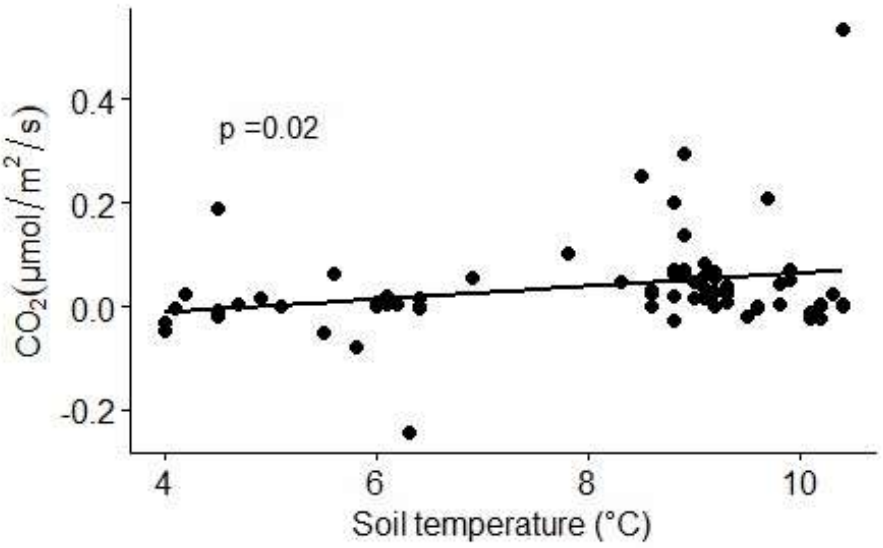


Figure 5: Scatterplot for regression between $CO_2$ flux and soil temperature ($p < 0.05$) over the three months.

### 3.2 Chemical properties of soil cover types

There was a significant difference in pH and a weak significant difference in C:N ratio among the three soil cover types with depth. However, no significant difference was observed for mean total nitrogen and soil organic carbon among the soil covers with depth (Table 3).

**Table 3**: Average values (mean ± standard error) for soil pH, % carbon (C), % nitrogen (N), and C:N ratio. Values with the same superscript(s) are statistically similar while those having different superscript(s) differ significantly at ($p<0.001$).

| Soil cover | Depth (cm) | pH | SOC (%) | TN (%) | C:N ratio |
|---|---|---|---|---|---|
| Control | 0-5 | 5.87 ± 0.04 $^{c}$ | 4.44 ± 1.76 $^{a}$ | 0.21 ± 0.08 $^{a}$ | 24.16 ± 2.47 $^{a}$ |
| Control | 5-10 | 5.96 ± 0.09 $^{bc}$ | 4.35 ± 0.71 $^{a}$ | 0.24 ± 0.05 $^{a}$ | 20.14 ± 1.42 $^{ab}$ |
| Bare ground | 0-5 | 6.10 ± 0.08 $^{ab}$ | 4.98 ± 0.45 $^{a}$ | 0.29 ± 0.01 $^{a}$ | 18.15 ± 1.01 $^{b}$ |
| Bare ground | 5-10 | 6.18 ± 0.08 $^{a}$ | 4.84 ± 0.63 $^{a}$ | 0.26 ± 0.04 $^{a}$ | 20.87 ± 0.27 $^{ab}$ |
| Biocrust | 0-5 | 5.86 ± 0.00 $^{c}$ | 4.10 ± 0.43 $^{a}$ | 0.20 ± 0.02 $^{a}$ | 21.40 ± 1.03 $^{ab}$ |
| Biocrust | 5-10 | 6.10 ± 0.06 $^{ab}$ | 3.85 ± 0.53 $^{a}$ | 0.19 ± 0.02 $^{a}$ | 22.29 ± 0.61 $^{ab}$ |
| Mixed ground | 0-5 | 5.93 ± 0.03 $^{c}$ | 5.34 ± 0.37 $^{a}$ | 0.30 ± 0.01 $^{a}$ | 18.76 ± 1.38 $^{ab}$ |
| Mixed ground | 5-10 | 6.10 ± 0.08 $^{ab}$ | 4.87 ± 1.00 $^{a}$ | 0.28 ± 0.06 $^{a}$ | 18.92 ± 0.20 $^{ab}$ |
| p-value | | <0.001 | 0.605 | 0.849 | 0.0642 |

At 0-5 cm depth, the bare ground had the highest pH at 6.10 and was significantly different from the other soil covers. At the 5-10 cm depth, the bare ground had the highest pH at 6.18 and was not significantly different from the mixed ground and the biocrust but significantly different from the control which had the lowest pH at 5.96.

There was no significant difference in soil organic carbon at the two depths among the soil covers. However, the mixed ground had the highest carbon content (5.34%) at the 0-5 cm depth. The biocrust had the lowest carbon content (4.1%) at the 0-5 cm depth and at the 5-10 cm depth (3,85%). There was a weak significant difference in the C:N ratio among the three soil cover types with depth. However, the control had the highest C:N ratio (24.16) at the 0-5 cm depth while the bare ground had the lowest C:N ratio (18.5) at the 0-5 cm depth.

There was no significant difference in total nitrogen at the two depths among the soil covers.

## 4. DISCUSSION

### 4.1 Carbon dioxide, methane fluxes, soil temperature and soil moisture

The mean $CO_2$ fluxes ranged in positive values. These results show that respiration processes were taking place at the time of measurement, or that there was carbon emission into the chamber and atmosphere. Considering fluxes, the measurements register both respiration (positive = emissions) and photosynthesis (negative = uptake). The small $CO_2$ uptake which occurred during measurement is assumed to be due to a probe- or measurement error. Most of the $CH_4$ measurements were negative, indicating uptake.

In March, the biocrust had the highest $CO_2$ and $CH_4$ mean fluxes, as well as the highest temperature and moisture. $CH_4$ flux increased with increasing soil moisture. This confirms that biocrust may account for biogeochemical processes such as $CO_2$ and $CH_4$ fluxes (He 2012). The high moisture and temperature favour microbial activities. Microbes are known to utilize organic C as a source of energy and to release $CO_2$ (Burgin et al. 2011).

In April, the mixed ground had the highest mean $CO_2$ flux, temperature and moisture. The biocrust had the highest mean $CH_4$. It has been found that biocrust respiration becomes activated at a suitable moisture range, and it will slow down when soil moisture decreases (Zhang et al. 2018). In May, moisture had the most significant effect among the soil covers. The bare ground had the highest mean moisture of 0.74 $m^3/m^3$.

According to the statistical regression analysis, there is a covariant relationship between soil temperature and gas fluxes, particularly significant to $CO_2$ flux. This is to be somewhat expected where a rise in soil temperature would activate certain dormant microbes that contribute to carbon emissions by soil respiration. This confirms a report that stated soil temperature and soil moisture as the major abiotic factors controlling soil $CO_2$ concentration (Maier et al. 2011). This shows that any small change in soil temperature has a profound effect on $CO_2$ fluxes. The findings demonstrate that carbon flux was regulated by soil temperature (Humphrey et al. 2021).

### 4.2 Soil physical and chemical properties

The pH range at the site could be described as slightly acidic (Ravikumar and Somashekar 2013). Generally, there was a significant difference in pH among the three soil covers ($p<0.001$) with depth. The higher pH values of the bare ground, biocrust, and mixed ground at 5-10 cm signify that they could control the solubility of nutrients compared to the covers with lower pH values. Total organic carbon plays a very important role since organic matter assists in the improvement of soil structure and water-holding capacity (Liu et al., 2019). The results showed

that there was no significant difference in soil organic carbon at the two depths among the soil covers. However. even though the measurements revealed no significant difference between the soil covers, there is the ability of Andosol soil to store large amounts of carbon due to its volcanic origin (Arnalds 2004).

Nitrogen (N) is one of the essential nutrients for plant photosynthetic capacity (Freschet et al. 2018). The results showed that there was no significant difference in soil organic carbon between the soil covers at the both depths. However, the mixed cover had the highest total nitrogen. The low nitrogen level of biocrust contradicts a report where biocrust significantly ($P < 0.01$) increased total N, CEC (Cation Exchange Capacity) and organic carbon (C) content of surface soils (Karimi et al. 2023). The soil carbon to nitrogen (C:N) ratio is important for soil fertility as it shows the direct relationship between soil organic carbon (SOC) and total nitrogen (TN). There was a weak significant difference in the C:N ratio among the three soil cover types with depth. However, the control had the highest C:N ratio while the bare ground had the lowest C:N ratio.

## 5. CONCLUSIONS AND RECOMMENDATIONS

There was no significant difference in $CO_2$ and $CH_4$ flux among the soil covers but a significant difference in $CO_2$ flux and soil temperature between months. Moreover, there was a significant difference in soil moisture with soil cover type. However, there was no significant difference in $CH_4$ flux among the soil covers and months. This indicates that any small change in soil temperature has a profound effect on $CO_2$ fluxes. There was a significant difference in pH and a weak significant difference in C:N ratio among the three soil cover types with depth. However, no significant difference was observed in mean total nitrogen and soil organic carbon with depth among soil covers.

The wet period of the year in which the study was carried out could have contributed to the weak response of the soil $CO_2$ and $CH_4$ fluxes. Ultimately, soil $CO_2$ fluxes were responsible for the positive feedback of soil respiration. Methane oxidation was responsible for nutrient uptake. These findings help understand the controlling mechanisms of $CO_2$ and $CH_4$ in reclaimed soil. However, the results from the study do not show significant differences in fluxes between biocrust, mixed cover, and bare soil. The knowledge of measurement methods and processes of biocrust acquired through this study could be used in reclamation of degraded or eroded lands in Ghana.

The positive and significant relationship of $CO_2$ between soil temperature and month seems to be promising and thus it will be important to study this relationship during other times of the year in future research. I also recommend identifying the microbes in biocrust and other soil covers in order to further improve understanding of the dynamics of these microbes, especially in different seasons.

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# APPENDICES

## APPENDIX 1

Basic statistics of soil parameters for soil cover type.

| Soil cover | Depth (cm) | Mean pH | Standard deviation | Standard error | Mean nitrogen | Standard deviation | Standard error |
|---|---|---|---|---|---|---|---|
| Control | 0-5 | 5.87 | 0.060 | 0.043 | 0.207 | 0.109 | 0.077 |
| | 5-10 | 5.96 | 0.137 | 0.098 | 0.237 | 0.072 | 0.051 |
| Mixed | 0-5 | 5.93 | 0.057 | 0.033 | 0.304 | 0.017 | 0.009 |
| | 5-10 | 6.10 | 0.135 | 0.078 | 0.277 | 0.099 | 0.057 |
| Ground | 0-5 | 6.10 | 0.044 | 0.078 | 0.295 | 0.022 | 0.012 |
| | 5-10 | 6.18 | 0.135 | 0.078 | 0.255 | 0.066 | 0.038 |
| Biocrust | 0-5 | 5.86 | 0.008 | 0.004 | 0.202 | 0.033 | 0.019 |
| | 5-10 | 6.10 | 0.107 | 0.062 | 0.186 | 0.041 | 0.024 |

Basic statistics of soil parameters for soil cover type.

| Soil cover | Depth (cm) | Mean carbon | Standard deviation | Standard error | Mean carbon-to-nitrogen ratio | Standard deviation | Standard error |
|---|---|---|---|---|---|---|---|
| Control | 0-5 | 4.444 | 1.755 | 1.242 | 24.16 | 3.49 | 2.47 |
| Control | 5-10 | 4.351 | 1.007 | 0.712 | 20.14 | 2.01 | 1.42 |
| Mixed | 0-5 | 5.335 | 0.633 | 0.366 | 18.76 | 2.39 | 1.38 |
| Mixed | 5-10 | 4.874 | 1.707 | 0.985 | 18.92 | 0.35 | 0.20 |
| Ground | 0-5 | 4.978 | 0.786 | 0.453 | 18.15 | 1.75 | 1.01 |
| Ground | 5-10 | 4.836 | 1.089 | 0.629 | 20.87 | 0.47 | 0.27 |
| Biocrust | 0-5 | 4.102 | 0.746 | 0.430 | 21.40 | 1.78 | 1.03 |
| Biocrust | 5-10 | 3.853 | 0.914 | 0.528 | 22.29 | 1.05 | 0.61 |

## APPENDIX II

Basic statistics of gas fluxes for soil cover type and months.

| Month | Soil cover | Mean CO2 | Standard deviation | Standard error | Mean CH4 | Standard deviation | Standard error |
|---|---|---|---|---|---|---|---|
| March | Mixed | 0.076 | 0.049 | 0.035 | -0.078 | 0.055 | 0.039 |
| March | Ground | NA | NA | NA | NA | NA | NA |
| March | Biocrust | 0.094 | 0.040 | 0.023 | -0.006 | 0.001 | 0.001 |
| April | Mixed | 0.044 | 0.030 | 0.017 | -0.040 | 0.014 | 0.008 |
| April | Ground | -0.001 | 0.035 | 0.020 | -0.071 | 0.096 | 0.055 |
| April | Biocrust | -0.028 | 0.038 | 0.021 | -0.036 | 0.011 | 0.006 |
| May | Mixed | 0.084 | 0.082 | 0.047 | -0.04 | 0.015 | 0.008 |
| May | Ground | 0.009 | 0.015 | 0.008 | -0.027 | 0.016 | 0.009 |
| May | Biocrust | 0.040 | 0.030 | 0.017 | 0.041 | 0.030 | 0.017 |

Basic statistics of soil temperature and soil moisture for soil cover and months.

| Month | Soil cover | Mean soil temperature | Standard deviation | Standard error | Mean soil moisture | Standard deviation | Standard error |
|---|---|---|---|---|---|---|---|
| March | Mixed | 8.783 | 0.112 | 0.068 | 0 | 0 | 0 |
| March | Ground | NA | NA | NA | NA | NA | NA |
| March | Biocrust | 8.811 | 0.244 | 0.141 | 0.56 | 0.025 | 0.014 |
| April | Mixed | 6.288 | 1.909 | 1.102 | 0.493 | 0.123 | 0.071 |
| April | Ground | 5.4555 | 1.202 | 0.694 | 0.493 | 0.113 | 0.066 |
| April | Biocrust | 5.322 | 0.952 | 0.550 | 0.4 | 0.132 | 0.076 |
| May | Mixed | 9.863 | 0.569 | 0.325 | 0.459 | 0.073 | 0.042 |
| May | Ground | 9.511 | 0.482 | 0.278 | 0.742 | 0.260 | 0.150 |
| May | Biocrust | 9.616 | 0.553 | 0.3192 | 0.426 | 0.012 | 0.006 |

## APPENDIX III

Results of one-way ANOVA of pH, soil organic carbon, total nitrogen, and C: N ratio regarding soil cover and depth.

| | pH F-value | pH p-value | SOC F-value | SOC p-value | Total N F-value | Total N p-value | C: N ratio F-value | C: N ratio p-value |
|---|---|---|---|---|---|---|---|---|
| Soil cover | 6.83 | <0.001 | 1.56 | 0.23 | 3.61 | 0.03 | 3.69 | 0.03 |
| Depth | 17.72 | <0.001 | 0.31 | 0.58 | 0.34 | 0.57 | 0.09 | 0.77 |
| Soil cover* Depth | 7.93 | <0.001 | 0.03 | 0.99 | 0.26 | 0.85 | 3.04 | 0.06 |

## APPENDIX IV

Results of one-way ANOVA for CO2 and CH4 fluxes, soil temperature, and moisture with regard to soil cover types in March, April, and May (TS=soil temperature, MS= soil moisture).

| Month | $fCO_2$ F-value | $fCO_2$ p-value | $fCH_4$ F-value | $fCH_4$ p-value | TS F-value | TS p-value | MS F-value | MS F-value |
|---|---|---|---|---|---|---|---|---|
| March | 0.119 | 0.739 | 1.254 | 0.283 | 0.051 | 0.825 | 187.3 | <0.001 |
| April | 3.229 | 0.057 | 0.774 | 0.472 | 1.549 | 0.233 | 1.826 | 0.185 |
| May | 0.165 | 1.92 | 1.094 | 0.348 | 2.006 | 0.153 | 13.28 | <0.001 |