GRÓ Land Restoration Training Programme
Árleynir 22, 112 Reykjavik, Iceland

Final project 2021

THE EFFECTS OF DEGRADATION ON SELECTED SOIL PARAMETERS AT THE SOGN PEATLAND SITE: A COMPARISSION OF PEATLANDS IN DIFFERENT STATUSES

Mamosa Mahlompho Nei
Ministry of Forestry, Range and Soil Conservation
Private Bag A039, Mokhotlong, Lesotho
lkoetle.nei@gmail.com

Supervisors
Dr Hlynur Óskarsson
Agriculture University of Iceland
hlynur@lbhi.is

Sunna Áskelsdóttir
Soil Conservation Services of Iceland
sunna@land.is

ABSTRACT

Peatland degradation has been a universal norm for centuries and has resulted in large amounts of CO2 being emitted into the atmosphere. Agriculture is the number one factor for peatland degradation in Lesotho and Iceland. Degradation influences hydrology of peatlands and increases oxidation of organic matter, contributing to greenhouse gas effects. However, natural peatlands represent large soil carbon reservoirs and groundwater storage. The study objectives were to evaluate groundwater levels and carbon stocks, and to quantify carbon dioxide fluxes in pristine, restored, and drained peatlands in the Sogn farm, South Iceland in order to adapt the evaluation approach to Lesotho circumstances. Data was collected randomly in three plots at 5-15 cm and 15-30 cm depths using a shovel. In addition, soil cores to measure carbon dioxide fluxes, water table depth, carbon content, soil organic matter, and bulk density were collected at 100 cm and 200 cm depth in the drained subsite using a soil auger. Soil organic matter was measured using Loss on ignition. A vario TOC cube was used to measure carbon content, and calibrated conduit PVC pipes were used to determine water level. The chamber method was used to determine carbon dioxide fluxes and bulk density was determined by the Bart method. The results showed that pristine and restored peatlands were statistically the same in terms of water table depth ($p > 0.59$), CO_2 fluxes ($p > 0.28$), and soil organic matter ($p > 0.33$), but there was a difference between pristine and drained sites, and restored and drained sites in WTD p

<0.001), CO_2 fluxes ($p < 0.001$), and SOM ($p < 0.001$). Carbon content ($p < 0.001$) between pristine and restored, pristine and drained and restored and drained peatland was significantly different. This study showed the importance of valuing peatlands, to stop their degradation and to conserve them. The value of restoring degraded peatlands through the rewetting method is clear. Rewetting is a cost-effective method to revive the peatlands in a short period.

Key words: Sogn, degradation, peatland, hydrology, greenhouse-gases

This paper should be cited as:

Nei MM (2021) The effects of degradation on selected soil parameters at the Sogn peatland site: A comparison of peatlands in different statuses. GRO LRT [final project] https://www.grocentre.is/static/gro/publication/829/document/nei2021.pdf

TABLE OF CONTENTS

ABBREVIATIONS

GHG	Greenhouse Gases
LOI	Loss on Ignition
C/N ratio	Carbon Nitrogen Ratio
BD	Bulk Density
WTD	Water Table Depth
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
MEA	Millennium Ecosystem Assessment
WI	Wetland International
COP	Conference of Parties
CO_2	Carbon Dioxide
CH_4	Methane
ORASECOM	Orange-Senqu River Commission
UNEP	United Nations Environment Programme
SOC	Soil Organic Carbon

1. INTRODUCTION

Wetlands are ecosystems of great importance and provide a range of services that can influence the lives of both man and other living organisms (Alexander & McInnes, 2012). These services include food production, energy production, recreational services, soil development, carbon sequestration, biochemical cycling, purification of water, prevention of droughts and floods, and protection against erosion, to name a few (Mitsch & Gosselink, 2015). Wetlands are valuable resources for the sustainable maintenance of biodiversity and are one of the landscape elements that store carbon (Senger et al. 2021).

However, Maljanen et al. (2010) stated that wetlands in their original state act as sinks of atmospheric CO_2 and a source of CH_4, but if exposed to draining, the condition is reversed. Draining of peatlands increases soil organic matter oxidation and organic nitrogen mineralization and increases nitrous oxide production (Augustin et al. 1998; Hu et al. 2017). In addition, increased organic matter oxidation leads to soil subsidence which is another factor of draining (Western et al. 1997; Hu et al. 2017). The breakdown of organic matter then follows two main pathways: aerobic and anaerobic states. Aerobic breakdown takes place in the aerated portion of the soil and releases CO_2. In waterlogged conditions, anaerobic breakdown results in the formation of methane (LAI 2009; Sundh et al 2000). Methane is formed in the anaerobic zone below the water table, but as it travels through the aerated part of the soil, a portion of it is oxidized by methanotropic bacteria (LAI 2009). However, CO_2 and N_2O in natural wetland areas are estimated to balance the emissions of CH_4, but the exact contributions of wetlands to GHGs variations are still under investigation.

Wetlands are valuable ecosystems which store carbon from the atmosphere belowground as they are characterized by soils with high organic carbon content. They are estimated to occupy 3% of the total land surface area worldwide and can store about 30% of the total global soil carbon pool (Parish et al 2008; Erwin 2009; Barthelmes & Joosten 2015; Dayathilake et al. 2021). They are an important component in the carbon cycle and climate regulation (Millennium Ecosystem Assessment 2005; Kimmel & Mander 2010). They form part of the habitat for numerous plant and animal species. The vegetation and plant biomass above and below the ground are the primary indicators of wetland health and signal their potential as a carbon sink (Collin 2005; Zhu 2010; Wetland International 2012).

Due to human actions on wetlands, their function has been disturbed, exposing wetlands soils to an aerobic state and hence, carbon dioxide emissions (Maljanen et al. 2010; IPCC Task Force on National Greenhouse Gas Inventories 2014). Again, this has led to the reduction of wetland areas which has directly affected wetland-dependent species, which are faced with reduced habitat availability and increased competition for food and other resources (WWF [Worldwide Fund for nature] 2016). With disturbance, wetlands often suffer reduced water table depth, converting the wetland soils from a sink for carbon dioxide to a source. They have also undergone a decline in their capacity to provide various services to man and the environment (Overpeck et al. 2013).

According to Alexander and McInnes (2012, p.2):

> [W]etlands are areas of marsh, fen, peatland, or water, whether natural or artificial, permanent, or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres.

Wetlands in Iceland have undergone severe degradation that has impacted negatively on their carbon stocks and biodiversity (Guðmundsson & Óskarsson 2014; Arnalds et al. 2016). The Environment Agency of Iceland (2021) reported that recent research has shown that the main source of CO_2 emissions within Iceland is drained wetlands. On the other hand, Arnalds et al. (2016) said that the still intact Icelandic wetlands are very fertile with higher bird nest density and distribution than neighbouring countries with similar wetlands. Their outstanding characteristics are the combination of the properties of andosols and histosols. They originally covered about 9,000 km^2 with very deep soils of 1-3 m in thickness, and they store large amounts of carbon.

Arnalds (2016) further stated that these wetlands have been subjected to intense draining through government subsidies to maximize agricultural production in the post-World War II era. The goal was to reduce population migration from rural to urban areas. Arnalds (2016) further noted that 47% of inland wetlands were drained through subsidies to increase agricultural land (haymaking) and grazing. The draining effort has been ongoing for more than 50 years without evaluating the impacts on the utilization of the drained lands, resulting in some drained areas being abandoned without being utilized as planned (Guðmundsson & Óskarsson 2014).

Similarly, Lesotho is no exemption to the challenge of wetland degradation and negative change on a carbon stock due to overgrazing and trampling on fragile wetlands to the point of extinction (Orange-Senqu River Commission 2018). Lesotho wetlands are severely degraded due to over-utilization. The land in Lesotho is owned publicly by the people, meaning that all pastoral administration is communally controlled. This has resulted in erosion in wetlands, change in carbon stock, loss of biodiversity, and change in the species composition of wetlands and the surrounding catchments (Du & Brow 2011).

The purpose of this research is to gain knowledge and skills on methods for quantifying disturbances in wetlands and design solutions to address the challenges in Lesotho. In this study, the wetlands of the Sogn farm in South Iceland were examined in terms of key soil parameters. The Sogn farm has peatlands in three different states: pristine, degraded and restored. The site was selected as the case study with relevance for Lesotho's restoration potential because the situation in this area is a comparative example of the wetland scenarios in Lesotho.

1.1 Wetland restoration and protection

The loss and degradation of wetlands has harmed humankind and other living organisms resulting in loss of carbon into the atmosphere, loss of fertile soils, and severe soil subsidence and contaminated water intrusion in floodplains and coastal areas (Ramsar Convention 2015). Therefore, to regulate and cool the global climate, restoration measures and protection of this ecosystem are vital (Fennessy & Lei 2018). In the UNFCCC (2011) it was said that rewetting is a very effective method for decreasing greenhouse gas emissions, and a cost-effective remedy to reduce them. Iceland, being a member of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, is expected to report annually on greenhouse gas sources and carbon storage. Therefore, the government of Iceland formulated a climate change policy that aims to reduce greenhouse gas (GHG) emissions and increase carbon sequestration levels through the rewetting method (Hellsing et al. 2018). The method of rewetting also applies to other wetlands across the world, and Lesotho is no exception to the benefits of rewetting this ecosystem.

Parish et al (2008) reported that at the seventh session of the Conference of Parties (COP7) held in Malaysia in 2004, methods for wetland restoration were proposed and approved for restoration potential in consideration of their significant value on the environment. The assessment indicated the importance of the ecosystem regarding biodiversity, provision of services, the critical role of sustaining livelihoods, and their role in greenhouse gas regulation (Ramsar Convention 2015). Furthermore, wetlands were perceived to be an environmental resource in mitigating climate change. According to the Ramsar Convention (2015), careful and wisely managed wetlands are great investments for long-term global climate change mitigation.

In contrast, wetland degradation has been shown to be the major contributing source of greenhouse gases. Therefore, to keep the global temperature increase below 2°C, mitigation strategies need to be executed without delay. According to UNEP (2019), achieving the 2°C Paris Agreement target could save the environment from the global predicaments and expenditure such as property destruction through floods, climate change effects, recurring health problems, poverty, and famine in some parts of the world. Therefore, the efficient conservation and sustainable use of natural peatlands and restoration of degraded peatlands must be a priority for a proper mitigation strategy with global impact.

1.2 Study objectives

Peatlands represent large soil carbon reservoirs and groundwater storage. Due to degradation and reduced water levels in wetland soils, certain soil parameters have been heavily impacted, resulting in dramatic changes in carbon stocks and their form by becoming the carbon source, hence adding to the greenhouse gas effects, and contributing to global warming. As a result, the objective of the study is to learn methods to quantify disturbances in peatlands and design solutions to address the challenges in Lesotho. There is also a critical need to evaluate selected soil parameters such as ground water, carbon stocks and CO_2 emissions on different peatland sites in the Sogn farm. For this reason, critical insight is needed in peatland degradation to bring to attention the importance of this ecosystem.

1.2.1 Specific objectives

The specific objectives of this study were:

- To estimate carbon stocks in the three different sites
- To compare water levels within the three different sites
- To measure CO_2 emission in the three different sites
- To learn methods of analysing wetland degradation for restoration potential in Lesotho.

Although the information given above is on wetlands in general, the focus of the study is mainly on peatlands. "[P]eatlands are wetlands in which peat (dead plant matter) accumulates due to slow decomposition" (Du & Brow 2011, p. 249). Peat is soil that accumulates partially decomposed organic matter from plant materials forming under waterlogging conditions. Saturated soils with high water levels create an anaerobic condition resulting in oxygen deficiency to facilitate the decomposition of organic matter (Parish et al. 2008). About half the world's wetlands are peatlands. They are present in all the parts of the world's regions. Peatlands are ecosystems with peat soils and are the most valuable type of wetland from the perspective of carbon storage and cycling (Du & Brow 2011, p. 249; Ramsar Convention on wetlands 2018).

1.3 Peatlands of Lesotho

The Lesotho peatlands are in the highlands, most extensively in the mountainous escarpment near the country's eastern border. The peatlands in Lesotho are unique soligenous fens, which are rare in the African continent (Trettin et al. 2008). They form an integral part of the mountain landscapes, with high elevation valley bottoms and side slopes, signifying the availability of water, alpine vegetation, and a favourable micro-climate to sustain the mire development.

They have a deep peat deposit that exceeds a range of 1-2.5 m depth and consists of organic material and water (Trettin et al. 2008). This ecosystem plays a vital role ecologically and economically in the country. They are a significant reservoir of carbon and contribute to local biodiversity. They form the headwaters of the Senqu (Orange) river that emanates from the high-altitude peatlands discharging clean water from Lesotho, South Africa, Botswana, and Namibia, making them the principal water reserve of Southern Africa (Grundling et al. 2015).

About 40% of the annual river flow is generated from the peatlands in the highlands of Lesotho. The clean water from the wetlands is traded to South Africa and contributes about 10% of the total GDP to the economy. Water is also used to generate hydroelectricity that is also exported. Due to their high alpine vegetation, and productive pasturelands, Lesotho peatlands are regarded as a critical grazing resource (Du & Brow 2011) However, overgrazing through overstocking has influenced severe gully erosion in the peatlands, which detrimentally threatened the pristine characteristics of this ecosystem in Lesotho. Access to land is open to every person subjecting the rights to land as communal and traditionally controlled by the Principal Chief whom in their power delegates authority to assign usage of the land, inclusive peatlands (Trettin et al. 2008).

The highlands are used almost entirely for livestock grazing and are viewed as an integral part of rural livelihoods. The impacts of overgrazing are evident in summer. Moreover, peatlands are regarded as part of the rangelands since they are enclaved at the bottom valley of these rangelands and are viewed as a source of drinking points for animals. Severe trampling of this ecosystem has resulted in compaction, severe gully erosion, extinction of native peatland species which are replaced by the invasive species known as *Chrysocoma ciliate (sehalahala)* which has invaded almost the entire rangelands (Du & Brow 2011).

Figure 1. Overgrazing and gully erosion in the peatlands of Lesotho.
(Source: From Du & Brow 2011).

Figure 2. Severe gully erosion of peat exposing gravel beds permeable to water. (Source: From Grundling et. al 2015).

Figure 3. Large scale erosion on the highland peatlands of Lesotho. (Source: From Du and Brow 2011).

Even though there is the challenge of over-utilization of these peatlands, the Lesotho government, through the ministries and academic world, are making efforts to address this problem. However, the results are insignificant considering the scale of damage compared to restoration measures. The processes of reviewing policies are very slow in producing a legal framework to protect rangelands as well as wetlands in general. On the other hand, effective and continuous restoration measures are needed to restore, sustain, and protect the capacity of these peatlands.

2. METHODS

This study was carried out using peatland soil samples collected on the first week of July 2021 across the Sogn farm, South Iceland.

This area was classified into three sub-sites or plots, pristine, restored, and drained peatland, to examine the impact of degradation on selected soil parameters of these three sub-sites.

2.1 Study area: Sogn Farm

Sogn farm is in the Ölfus municipality, South Iceland 63°59'40.02"S - 21°7'59.09"W. Cultivation of fields for hay production has been abandoned for decades, and the farm has been used for horse grazing. The estimated terrain elevation above sea level is 60 meters. However, the age of the drainage is unknown, but ditches were already present in 1977 as shown in Figure 4 below.

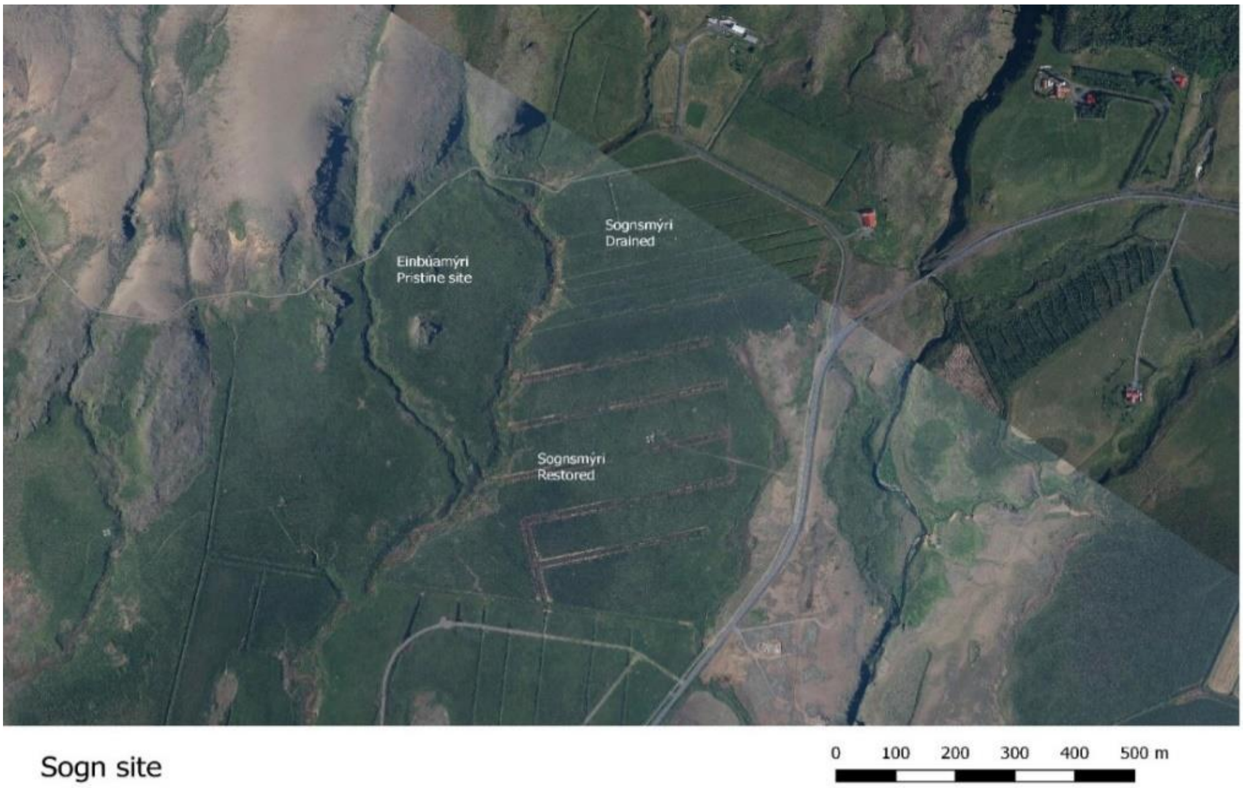

Figure 4. Sogn Farm South Iceland. The locations of the pristine, restored, and drained peatland sub-sites are indicated. (Source: S. Áskelsdóttir 2021).

2.2 Experimental design, sampling, and classification of the peatlands

Three subsites were selected: pristine, restored, and drained. Soil samples were taken randomly within the three plots for two consecutive days. At each plot, holes were dug with a regular shovel at plough layer level and samples were collected and separated at two depths intervals 5-15 cm, 15-30 cm, and soil cores at 100 cm to 200 cm depth only on the drained sub-site using extendable soil auger. When sampling the sward layer, 0-5 cm was removed. Bulk density and soil samples were taken in all the different depths of the three sub-sites.

Wells were established for measuring soil water table depth or level (WTD) with a soil corer (5 cm width) which was done only once due to time limit. Calibrated conduit PVC was used to determine water levels in the drained site. The pipe was inserted in a hole and blown to detect the water level then measurements were taken. On the wet sites the water level was at the surface or beneath the surface, so a ruler was used to measure the level.

The pristine (healthy) peatland was exhibiting notably high water table levels at the surface, and regional biodiversity characterised by species such as cotton grass (*Eriophorum angustifolium*) and sponge-like soil dominated by soil organic matter (SOM). The drained site was visibly recognizable by enormous drainage ditches.

The absolute conversion of peatland into predominant grassland for hay production and constantly low water levels below 125 cm, were evident by degradation of that peatland site, while the restored peatland was determined by rewetted ditches, litter material from hay grasses, and some primitive wetland species of bog pins (*Eriocaulon decangulare)* emerging. Some parts of the area were waterlogged due to the recharge from rewetted ditches. The water table levels were measured once at each site on the first week of July.

2.3 Measurements

2.3.1 Bulk density

Holes were dug in the peatlands and flat vertical surfaces were prepared. A bulk density sampler was pressed into the soil on the drained peatland. The sample was removed by cutting around the outside edges of the cylinder with a knife and holding a turf cutting knife (blade) underneath to carefully lift it out. Excess soil was then removed from both sides of the cylinder with the knife. On the pristine and restored peatlands, bulk density samples were obtained using different equipment. The soils there were complete peat (plant material matter) so the cylinder ring could not cut through to extract the samples. Instead, a blade was used to cut a brick of peat. 125 cm^3 were cut from the brick of peat to obtain bulk density samples for these peatlands (Bart 2004, Brady et al 2004). A total of 24 samples were collected for bulk density.

The samples were then placed in a sealable bag and labelled accordingly for laboratory analysis. An empty aluminium cup for each sample was used. It was first measured on the scale and the weight was recorded. Then, samples were placed in the aluminium cups of known weight. Sample weights were also recorded before drying. The samples were oven-dried at 105^oC for 24 hours and the oven-dry weight recorded. Samples were then sieved through a 2 mm sieve. Two fractions (< 2 mm and > 2 mm) were obtained and weighed. Then the volume of the > 2 mm fraction was measured, and this volume was subtracted from the total volume of the sampling cylinder. Bulk density was then calculated by the formula below (Bart 2004; Brady et al 2004).

$$Db = \frac{ODW}{(WW-CF)}$$

Where:

Db = Bulk density of < 2mm (g/cm^3)
OWD = Oven-dry weight
WW = Wet weight
CF = Weight of coarse fragments

2.3.2 Carbon Content (% C)

Soil samples were air-dried at about 40°C and then sieved through a <2mm sieve for further measurements. Sub-samples were then ball milled to obtain the homogenous texture using a Retsch PM 400 ball mill machine, then encapsulated in a tight plastic container for carbon analysis. Ball mills were cleaned with ethanol between the samples. The ball milled samples in a tube were then taken to another laboratory for carbon analysis. Samples were weighed in tin foil containers. The foil was then wrapped around each sample and the resulting pack was pressed into a pill with a special press. The purpose of the tin foil was to contain the samples and to further improve the combustion of the samples.

Samples were weighed to a specified value of 0.15 g which is a standard value for soils with high organic carbon content. Otherwise, the sample sizes can vary depending on the soil type. When weighing the samples, surfaces and utensils were cleaned by wiping with dry and clean paper to avoid contamination between samples. A petri dish was used to place pressed samples on for measurement. It was weighed first and then tarred. The pressed samples were then placed in a tarred dish back on an analytical balance scale to assess the added mass and every weight was recorded to four decimals. The pill samples were then placed on a labelled auto sampler ready for carbon analysis with the Elementar Analysensysteme GMBH, Hanau method (Vario TOC cube) where the samples were ignited at 950^{o}C to measure carbon as gas. The remaining parts of the samples were weighed, then oven-dried at 105^{o}C for 24 hours, before being weighed again to use for dry matter correction of the carbon results.

Where:

Dry matter (DM) = dry sample/ wet sample.

Carbon content (%C) = results/ DM

2.3.3 Loss on Ignition

The Loss on Ignition method can be used to estimate soil organic matter in soils. Clean and dry porcelain crucibles were marked outside with a permanent marker for easy identification and weighed. The weight was recorded. Oven-dry samples were then added to the crucibles and the weight of the crucible plus soil sample was recorded. Oven dry samples were placed in a furnace at 550^{o}C for four hours. At this point, organic matter is burned off and excess water is lost. The mass loss between the two temperatures is loss on ignition. The percentage loss on ignition is determined by dividing the initial loss on ignition by the mass of oven-dry soil multiplied by 100 (Rowell 1997).

% LOI = 100 * (mass of oven-dry soil-mass of ignited soil)/ mass of oven dry soil.

Where:

% LOI = percent loss on Ignition

2.3.4 CO_2 flux

Ecosystem CO_2 emission (respiration) was measured using the chamber method (Lundegårdh 1927). A chamber is used for trapping gas emitted from plants and soil within and below the chamber. The change in the CO_2 concentration in the chamber was measured with an attached

EGM portable gas analyser (PP systems, Amsesbury, MA, USA). The chamber used in this study was dark (covered), had a volume of 2,427 ml and surface area of 167 cm^2. For each measurement, CO_2 concentration readings were recorded at one-minute intervals during an incubation period of two minutes. When measuring CO_2, I assumed temperature as constant between areas since measurements were done at all three sites for five hours within the same day.

2.3.5 Data analysis

R statistics was used to run a simple linear regression with factors to compare the effects of an independent variable on the dependent variables, where peatland degradation was the independent variable and the dependent variables were the following soil parameters: BD, LOI, % C, WTD, and CO_2 fluxes on the pristine, restored, and drained peatlands. Linear regression was used to check the response of soil parameters to degradation in peatlands of different statuses. Data was filtered and sorted using Microsoft excel before running it through RStudio.

3. RESULTS

3.1 Water table levels

The range of water table depth values for pristine, restored, and drained sites was -1.3 cm, -6.5 cm, and -125 cm respectively, demonstrating a trend of increasing water table depth from pristine peatland sites to the restored sites. The most pronounced decrease of water table depth was in the drained sites. The water levels in the pristine and restored peatlands proved to be non-significantly different with $p > 0.59$, while the difference between the pristine and drained peatlands was highly significant ($p < 0.001$). There was also a highly significant difference in water table depth between the restored and drained peatlands ($p < 0.001$) as indicated by the Figure 5 below.

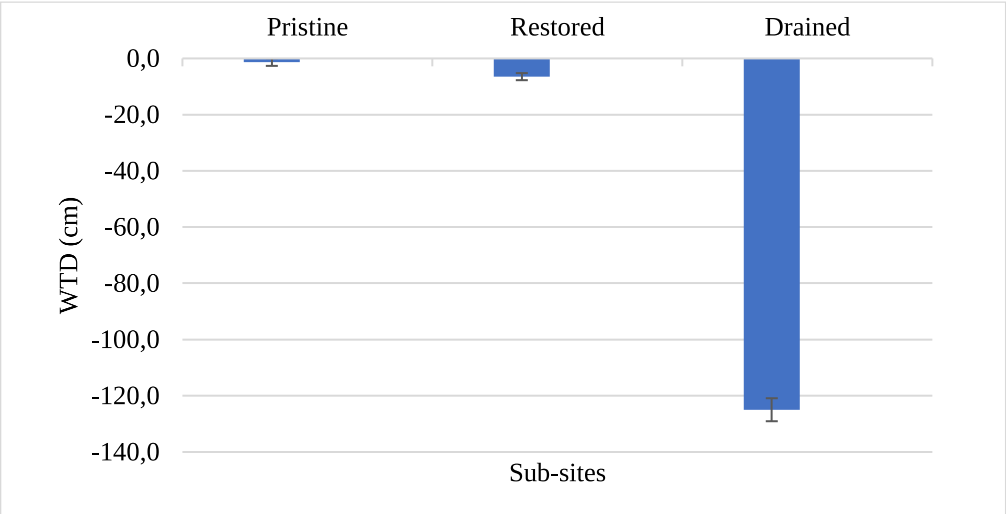

Figure 5. Water table level in pristine, restored, and drained sites. Bars represent the standard error of the mean.

3.2 Bulk density

Bulk density values for the 5-15 cm soil layer ranged from as low as 0.21 g/cm^3 in the very organic rich soils found in the pristine peatlands, 0.25 g/cm^3 in the restored peatlands, up to as high as 0.59 g/cm^3 in drained peat (Figure 6). There was a significant difference between the pristine and restored peatlands (p-value < 0.004), while the differences between the pristine and drained peatland, p < 0.001, and restored and drained peatland, p < 0.001, were highly significant. Within the 15-30 cm soil layer, the bulk density in pristine, restored, and drained peatland was 0.21 g/cm^3, 0.25 g/cm^3 and 0.69 g/cm^3 respectively. The difference in bulk density between the pristine and restored peatlands was non-significant (p > 0.55), while the differences between the pristine and drained peatlands, p < 0.001, and between restored and drained peatlands, p < 0.001, were highly significant.

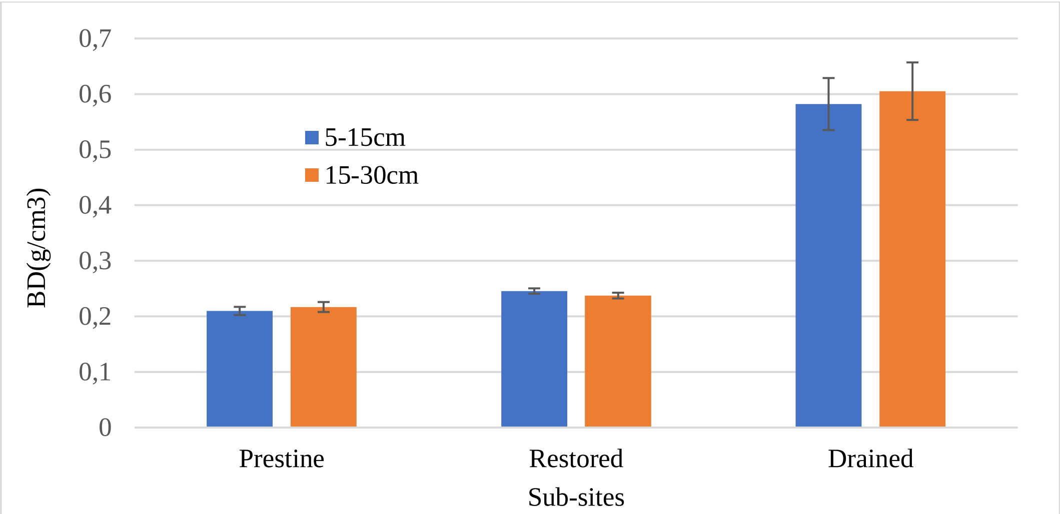

Figure 6. Soil bulk density of pristine, restored, and drained sites. Bars represent the standard error of the mean rate.

3.3 Loss on Ignition

In the 5-15 cm layer, the difference in soil organic matter content between pristine and restored peatlands was non-significant, p > 0 .33, while the differences between pristine and drained, p < 0.001, and between restored and drained peatland, p < 0.001, were highly significant. In the 15-30 cm layer there was a significant difference between the pristine and restored peatland, p < 0.001. The difference between pristine and drained peatland, p < 0.001, and between restored and drained peatland, p < 0.001, were highly significant as indicated by Figure 7.

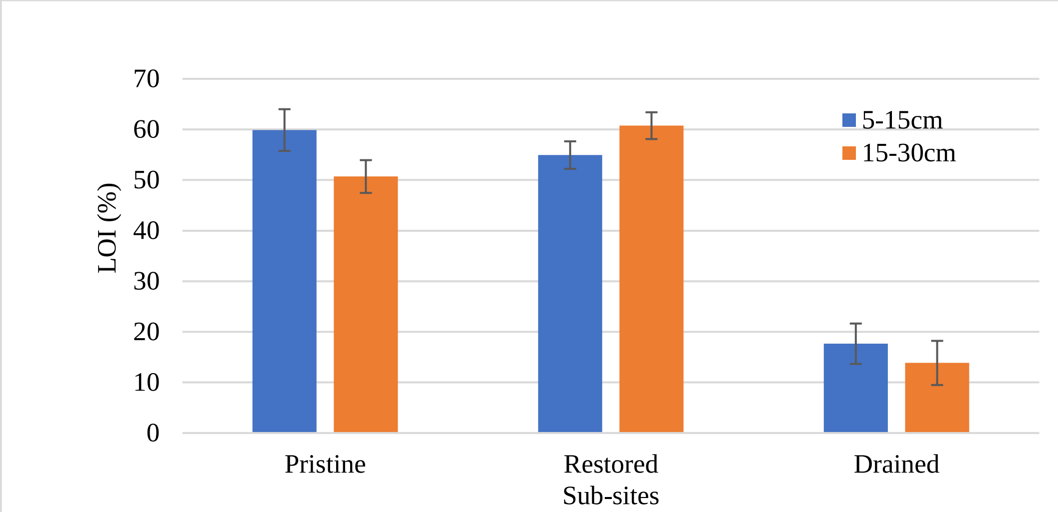

Figure 7: Loss on Ignition for pristine, restored, and drained peatland. Bars represent the standard error of the mean.

3.4 Carbon content

As shown in Figure 8, in the 5-15 cm layer, the differences in carbon content between pristine and restored ($p < 0.001$), pristine and drained ($p < 0.001$), and restored and drained peatland ($p < 0.001$) were highly significant. In the 15-30 cm layer, there was a non-significant difference between the pristine and restored peatland ($p > 0.67$). The differences between pristine and drained, $p < 0.001$, and between restored and drained peatland, $p < 0.001$, were highly significant.

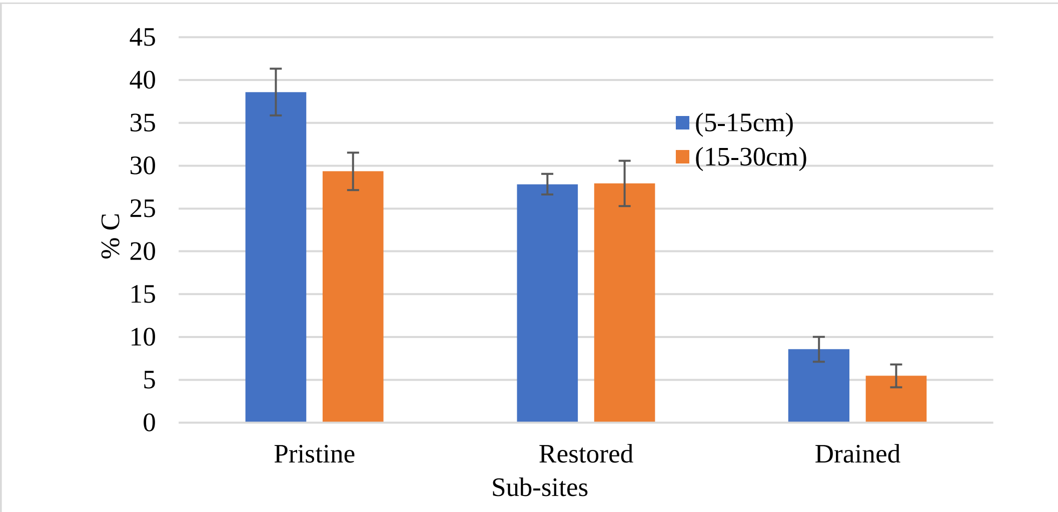

Figure 8. Carbon content in pristine, restored, and drained peatland. Bars represent the standard error of the mean.

3.5 CO_2 fluxes

Mean CO_2 respiration rate of the drained peatland was much greater at 889.9 mg/m^{-2}/hr^{-1} than that of the pristine peatland at 429.4 mg/m^{-2}/hr^{-1} and restored peatland at 340.9 mg/m^{-2}/hr$^{-1.}$ There was a non-significant difference in CO_2 fluxes of the pristine and restored peatlands, p >

0.28, while the fluxes of the pristine and drained, $p < 0.001$, and the restored and drained peatlands, $p < 0.001$, were significantly different (Figure 9).

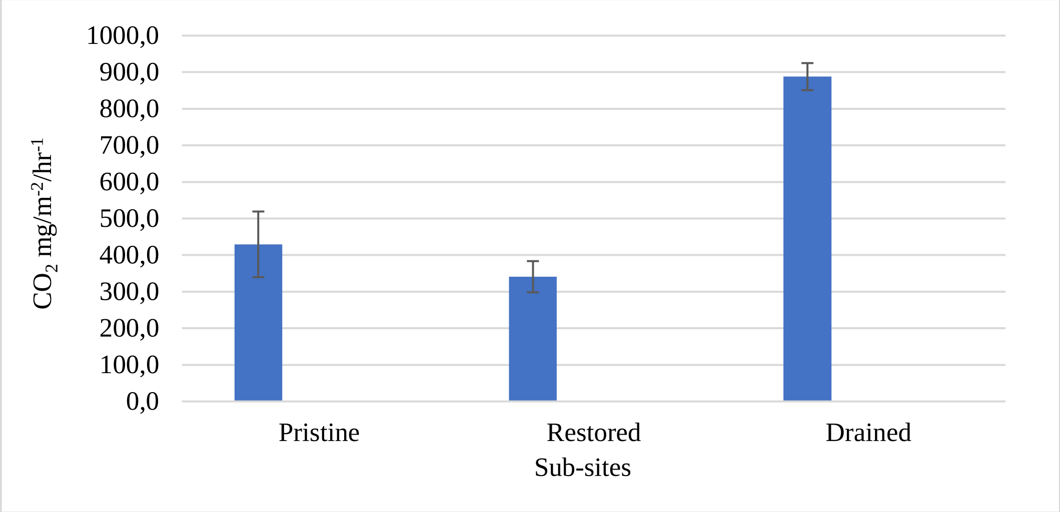

Figure 9. CO_2 fluxes of pristine, restored, and drained peatland. Bars represent the standard error of the mean.

3.6 Variability in soil BD, SOM and %C with depth in the drained peatland

As shown in Figures 10 a, b, and c there was a large decrease in bulk density and an increase in organic matter content as determined by the LOI method, and carbon content at 100 cm depth. However, statistically there was no evidence of a linear trend between the three variables. Nevertheless, the visual observation along the trends indicated an inverse change of these variables at the 100 cm level.

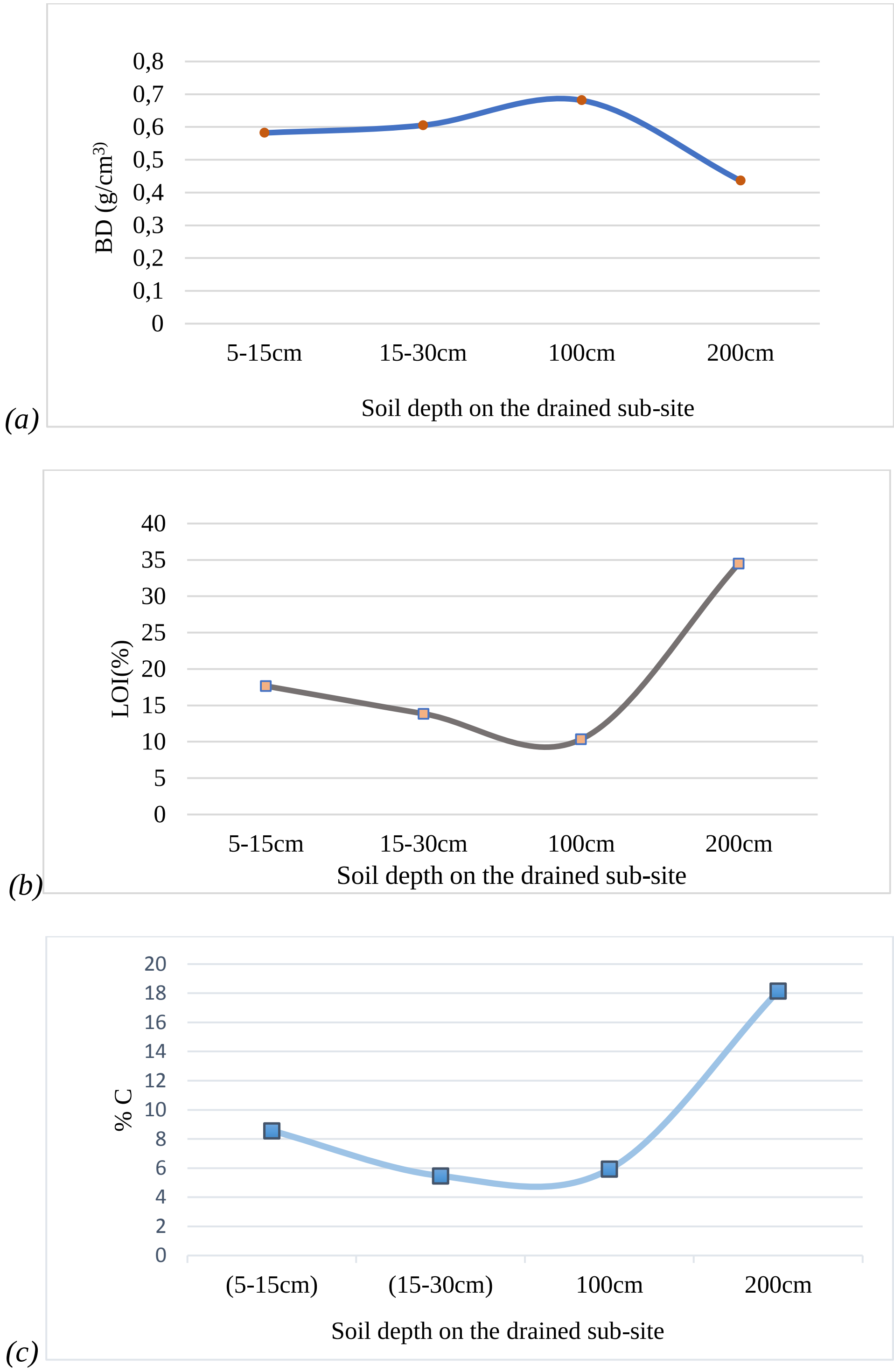

Figure 10 a, b, & c. Inverse changes in bulk density (BD), Loss on Ignition (LOI), and carbon content (%C) with increasing soil depth on the drained peatland of the Sogn sub-site.

4. DISCUSSION

The restored sub-site was not as degraded as the drained sub-site. It was only used as a horse grazing area and the restoration on this sub-site was very recent as it was executed in 2019. However, all functions of the natural peatland on the restored sub-site were not fully exhibited.

The drained sub-site had been totally converted into agricultural fields in the past four decades and grazed for about 20 years according to aerial photos. However, farming had been abandoned for about ten years.

4.1 Water table level and CO_2 fluxes

This study showed that carbon dioxide emission was strongly related to the water table depth in each of the three peatlands. Pristine and restored peatland were not significantly different in terms of water table depth and CO_2 fluxes. However, WTD and CO_2 fluxes between the pristine and drained and between restored and drained peatland were significantly different. CO_2 fluxes and water level at the surface of the pristine and restored peatland showed some constant balance in these ecosystems. The water level was at the surface of the peatlands resulting in low CO_2 emissions. However, in the drained peatland, degradation influenced CO_2 fluxes as the water table was lower. The pronounced CO_2 increase was evident as the water level was at lower depths of the profile. At this site, large amounts of carbon dioxide were emitted relative to the pristine and restored sites.

The main reason for this was the ditches constructed around the peatland, along with cultivation and compaction using machinery. Several studies have shown that the water table depth influences the fluxes of CO_2 in peatlands in a linear relationship (Moore & Knowles 1989; Maljanen et al., 2010). A change in fluxes through the rise in the water table level in a peatland in its natural state renders the soil in an anaerobic condition thereby slowing down aerated microbial decomposition rates, while drainage results in soil organic matter decomposition and CO_2 release (Hendriks et al. 2007). The rewetting method, used in the restored peatland, seemed successful in reducing the level of subsidence occurring and thus reversing the biochemical processes in the drained peatland into the functions prevalent in natural peatlands. Water levels were almost at the surface in the restored peatland, regulating the CO_2 emissions.

4.2 Correlation of some soil parameters for different peatlands statuses

The results showed that soil organic matter content in pristine and restored peatlands was statistically the same, while SOM in pristine and drained, and restored and drained peatlands was statistically different. Loss on ignition was used to detect changes in carbon cycling in the three peatland sites. LOI is one of the methods used to estimate soil organic matter content. Soils in the pristine and restored peatlands were flooded, resulting in a high accumulation of organic matter. With ongoing oxidation of soil organic material in the drained site, considerable change was expected in the soil as indicated by the LOI results. A lower organic matter content in drained sites indicated a greater portion of mineral content in the soil. Other studies confirm that peatlands accumulate large amounts of biomass in thick organic soil horizons with slow rates of decomposition due to anaerobic conditions while draining results in a high rate of decomposition of organic matter and loss of carbon as CO_2 into the atmosphere, and hence a relative increase in the soil mineral portion (Moore & Knowles 1989; Commons 2008; Maljanen et al. 2010).

The low water table in the drained peat soil of Sogn farm caused soil decomposition indicating a change in soil organic matter. Additionally, the bulk density of the pristine and restored peatlands was significantly different. Again, the bulk density of pristine and drained, and restored and drained peatlands was significantly different. Pristine and restored peatland soils were light in compaction. The soils were mostly peat (plant material matter). This means their bulk density was very low due to high organic matter and carbon content. However, the conversion of peatland through draining and cultivation in the past four decades caused degradation through soil mineralization.

The drained peatland had a very high bulk density. Other similar studies confirm that a higher concentration of organic matter reduces bulk density because it contains less dense plant and animal remains as compared to more dense minerals (Erdal 2012). Again, pristine peatlands exhibit thick and rich organic soils and have high water contents and carbon content with low values of bulk density (Erdal 2012).

Peatland soils in their natural state play an essential role in regulating anthropogenic greenhouse gases. Peatlands constitute the largest carbon pool in the terrestrial ecosystem but when drained they become a source greenhouse gas emission (Maljanen et al. 2010). This study showed that carbon content (%C) in pristine, restored, and drained peatland was significantly different statistically at a depth of 5-15 cm. The drained peatland was used for hay production and grazing, and the restored peat site was a horse grazing area. According to the findings of this paper, pristine peatland showed the exact characteristics of a natural peatland, while the drained peatland was highly oxidized. However, at the depth of 15-30 cm, the carbon content of the pristine and restored peatlands was not significantly different while the carbon content of pristine and drained, and restored and drained peatlands was different. Erdal (2012) indicated that there is a link between carbon content, organic matter, and soil moisture. As soil water increases carbon content also increases. An increase in organic matter in the soil indicates an increase in organic carbon resulting in a decrease in bulk density.

4.3 Variability in soil BD, SOM and %C with depth in drained peatland

The soil organic matter, carbon content and bulk density exhibited an inverse response as the soils with high organic carbon and water saturation tend to be light in weight, indicating the low bulk density of the soils. However, at 200 cm depth, the soil was observed as organic peat and the profile was buried in water. In the drained peatland, excessive tillage had destroyed the soil organic matter and carbon storage and weakened the natural stability of the soil aggregates. Tillage and the use of heavy equipment had resulted in compaction of the soil, hence increasing the bulk density. The soil water table level was also affected by the loss of organic matter and carbon and compaction, as it is known that organic matter increases soil's ability to hold water. Compaction increased bulk density and reduced the total pore volume, reducing the water holding capacity as identified by visual observations and laboratory results. However, statistically there was no linear relationship between the three variables. The impression was that for results below 300 cm depth, the evidence of a linear relationship between the three variables would be shown. These three parameters were observed beyond 100 cm in the drained peatland, but with the pristine and restored peatlands, the peat on that level was deep in water and it was impossible to extract the soil.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study shows that the degradation of peatlands emits a significant amount of CO_2 into the atmosphere, and changes both the structure of the peatland functions and their ecosystem services. Agriculture is one of the factors involved in peatland degradation in Lesotho and Iceland. Peatlands have been drained for hay production, grazing, and building infrastructure in Iceland, while those of Lesotho are overgrazed by livestock. Degradation influences peatland hydrology, resulting in hydrological changes like drainage, erosion, and groundwater abstraction. These lead to greenhouse gas emissions and changes in peat thickness due to oxidation and compaction (subsidence).

Drainage affects water regulation capacity hence water availability or eventual scarcity. Subsidence causes increased and prolonged flooding and affects the ecological character of the peatland. Gullies protrude through the peatlands due to degradation and erosion. These gullies then serve as ditches to drain the peatlands resulting in oxidation and further erosion. The effects from the impairment of the peatlands' carbon and water storage capacity and their filtering and erosion control role, the connected biodiversity loss, and disturbed distribution patterns are massive and costly. This condition exposes the peat to direct solar radiation, wind, and water erosion and affects the resilience of the population inhabiting the peatland areas.

The International Conventions and Conference of Parties meetings (COP) has approved the restoration of peatlands through the method of rewetting. Rewetting is a cost-effective method to combat the degradation of peat. Research has also showed that rewetting restores the natural state of the peatland and reduces soil respiration. It is also a possible strategy in mitigating greenhouse gas emissions within the Kyoto protocol. In this case study, the history of land use in the Sogn farm revealed a massive conversion of peatland into agricultural fields.

The results confirmed that drained peatlands are a source of greenhouse gas effects. The pristine peatlands bury carbon deep within their organic soils. They occupy only a fraction of the earth's surface (3%) but can store 30% of its carbon. The results from the restored site indicated the effectiveness of rewetting with fruitful results in the short period of two years since restoration. Therefore, this study provides a take-home message about possible methods for the restoration of peatlands in Lesotho. The peatlands of these two countries have many similarities with marshes, bogs, and fens of similar soil properties.

However, their land uses are quite different. Icelandic peatlands are cultivated for hay production, while Lesotho peatlands are part of the rangelands. This paper presents scientific evidence on the degradation of peatlands, the impacts and causes of degradation, and the need for restoration. In Lesotho, alarming peatland degradation is occurring at present. If remedial measures are not developed soon, these peatlands will erode even further and diminish in Lesotho's landscape.

5.2 Recommendations

I strongly recommend the government of Lesotho, land managers, and all stakeholders to take serious action regarding peatland ecosystems. Below are some specific recommendations:

Peatlands play a significant role in mitigating climate change effects. Their conservation and management are also crucial in the context of water scarcity. Therefore, it will be essential to engage in continuous education and awareness-raising on conservation, restoration, and wise use of peatlands.

It is necessary to provide finance for research since the loss of wetland function still needs to be determined and greenhouse gas emissions reduced. Leaders should prioritize special funds to upscale wetland restoration in Lesotho.

The success of halting degradation and further loss of peatlands in Lesotho, among other things, is dependent on law enforcement, so policymakers have to speed up the process of issuing the Range Management Resources Act. Huge peatlands in Lesotho should be officially declared and gazetted under the Ministry of Environment for protection. Furthermore, enforced implementation of already existing policies and legal frameworks should be ensured without prejudice.

To promote restoration and protection of the peatlands, all stakeholders should be informed about the impact of peatland degradation and the consequences as well as the **need** to restore and protect them.

Develop and implement a consolidated long-term restoration plan and strategy as one of the prospects for the conservation and rehabilitation of the peatlands in Lesotho. All stakeholders must be actively involved with their roles and responsibilities clearly defined for accountability.

Wetlands and peatlands can be the source of economic opportunities through community-based resource management. They can also create businesses associated with ecotourism, such as adventure tourism, bird watching, trekking etc. Therefore, there is a need to preserve wetlands and implement sustainable land-use practices to maintain and improve the quality of highlands, and also to support continued livestock grazing.

Lesotho is a semi-arid and semi-humid region, meaning the peatlands draw water from the underground and adjacent flows from the hillslopes. From my experience, restoration of these ecosystems has never been a success since the focus was only on the heart of the peatlands, disregarding the already degraded adjacent areas. Therefore, I recommend that, for restoration to be a complete success, the demarcation of peatlands should address the whole catchment and related landscapes as part of the restoration strategy.

ACKNOWLEDGEMENTS

I would like to thank my supervisors Hlynur Oskarsson and Sunna Askelsdóttir for their invaluable and constructive guidance, advice, and contributions; your good attitude, informed suggestions and support that made my research a well-articulated paper according to the GRO LRT standard.

I would also like to give heartfelt gratitude to Brita Berglund for her coordination, optimistic and straightforward views that shaped me to perform better when conducting this study, and the awesome feedback she contributed to my work.

I also thank the managers of the GRO Land Restoration Programme for their unwavering support in everyday life in Iceland, and the Ministry of Forestry, Range and Soil Conservation-Lesotho for considering me for this program and awarding me study leave.

My appreciation also goes to Maria Svavarsdorttir, Baldur Jon Vigfusson, my lab specialists who taught me all about the laboratory, and their diligent support to obtain results that shaped this paper today.

Arni Hafstad Arnorsson and Thorhildur Isberg for their diligent support in collecting data and analyzing the samples in the laboratory for me to complete this research paper.

I also appreciate you, Ölvir Styrmisson, for the constructive support you showed me when analysing my results with R statistics.

I give my sincere appreciation to the lecturers, who facilitated the impeccable and useful information that shaped me into a better and more informed individual and servant for Lesotho.

Lastly, I thank my fellows; they added memories to my experience in Iceland.

LITERATURE CITED

Alexander S, McInnes R (2012) The benefits of wetland restoration. Ramsar Scientific and Technical Briefing Note No. 4. Ramsar Convention Secretariat, Gland

Adhikari S, Bajracharaya RM, Sitaula BK (2009) A Review of carbon dynamics and Sequestration in Wetlands. Journal of Wetlands Ecology:42–46

Arnalds O, Orradottir B, Aradottir AL (2013) Carbon accumulation in Icelandic desert andosols during early stages of restoration. Geoderma 193–194:172–179

Arnalds O, Gudmundsson J, Oskarsson H, Brink SH, Gisladottir FO (2016) Icelandic inland wetlands: Characteristics and extent of draining. Wetlands 36:759–769

Augustin J, Merbach W, Rogasik J (1998) Factors influencing nitrous oxide and methane emissions from minerotrophic fens in northeast Germany. Biology and Fertility of Soils 28:1–4

Barthelmes A, Joosten H (2015) Peatlands and Climate in a Ramsar context. Page Peatlands and Climate in a Ramsar context. Nordic Council of Ministers, Copenhagen

Bart B (2004) Soil Survey Laboratory methods Manual, Soil Survey Investigating Report. version 9. Pages 40-42

Brady CN, Weil RR (2004) Elements of the Nature and Properties of Soil. Soil architecture and physical properties 2nd edition. Pages104-108. Pearson, New Jersey

UNFCCC (United Nations Framework Convention on Climate Change) (2011) Consideration of further commitments for Annex I Parties under the Kyoto Protocol Draft decision proposed by the Chair. Work:1–10

Chatanga P, Sieben EJJ (2019) Ecology of palustrine wetlands in Lesotho: Vegetation classification, description, and environmental factors Koedoe 61(1), a1574. https://doi.org/10.4102/koedoe.v61i1.1574

Collins NB 2005, Wetlands: The basics and some more, Free State Department of Tourism, Environmental and Economic Affairs, Bloemfontein https://www.dwa.gov.za/iwqs/rhp/provinces/freestate/wetlands basics&more.pdf.

Moore PK (2008) Quantifying Soil organic carbon (SOC) in wetlands impacted by groundwater withdrawals in West Central Florida. Master's Thesis, University of South Florida, West-Central Florida. https://scholarcommons.usf.edu/etd/456

Dayathilake DDTL, Lokupitiya E, Wijeratne VPIS (2021) Estimation of soil carbon stocks of urban freshwater wetlands in the Colombo Ramsar Wetland City and their potential role in climate change mitigation. Wetlands 41:29. https://doi.org/10.1007/s13157-021-01424-7

Dixon MJR, Loh J, Davidson NC, Beltrame C, Freeman R, Walpole M (2016) Tracking global change in ecosystem area: The Wetland Extent Trends index. Biological Conservation 193:27–35

Du PJ, Brow LR (2011) Impact of Domestic Animals on Ecosystem Integrity of Lesotho High Altitude Peatlands. Ecosystems Biodiversity. http://www.intechopen.com/books/ecosystems-biodiversity/impact-of-domestic-animals-onecosystem-integrity-of-lesotho-high-altitude-peatlands

Environment Agency of Iceland (2021) Ntational Inventory Report: Emissions of greenhouse gases in Iceland from 1990 to 2019, Reykjavik.

Erdal Sakin (2012) Organic carbon organic matter and bulk density relationships in arid-semi arid soils in Southeast Anatolia region. African Journal of Biotechnology 11

Erwin KL (2009) Wetlands and global climate change: The role of wetland restoration in a changing world. Wetlands Ecology and Management 17:71–84

Fennessy SM, Lei G (2018) Wetland restoration for climate change resilience. Ramsar:1–11

Finlayson CM, Davis JA, Gell PA, Kingsford RT, Parton KA (2013) The status of wetlands and the predicted effects of global climate change: The situation in Australia. Aquatic Sciences 75:73–93

Gardner RC, Barchiesi S, Beltrame C, Finlayson CM, Galewski T, Harrison I, Paganini M, Perennou C, Pritchard D, Rosenqvist A, Walpole M (2015) State of the world's wetlands and their services to people: A compilation of recent analyses. Ramsar Briefing Note no. 7. Gland, Switzerland

Grundling PL, Linström A, Grootjans AP, Grootjans AP (2015) Mires in the maluti mountains of Lesotho. Mires and Peat 15:1–11

Guðmundsson J, Óskarsson H (2014) Carbon dioxide emission from drained organic soils in West-Iceland. Soil carbon sequestration for climate food security and ecosystem services:155-159

Hellsing VÚL, Ragnarsdóttir AS, Jónsson K, Andrésson K, Jóhannsson Þ, Guðmundsson J, Snorrason A, Þórsson J (2018) National Inventory Report: Emissions of greenhouse gases in Iceland from 1990 to 2014:412

Hendriks DMD, Van Huissteden J, Dolman AJ, Van Der Molen MK (2007) The full greenhouse gas balance of an abandoned peat meadow. Biogeosciences 4:411-424

Hu J, VanZomeren CM, Inglett KS, Wright AL, Clark MW, Reddy KR (2017) Greenhouse gas emissions under different drainage and flooding regimes of cultivated peatlands. Journal of Geophysical Research: Biogeosciences 122:3047-3062

IPCC. (2014b). 2013 Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories. In: Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda, M. Troxler TG (eds) Wetlands. IPCC, Switzerland

Joosten H, Clarke D (2002) Wise use of mires and peatlands-Background and principles including a framework for decision-making. International Mire Conservation Group and International Peat Society, Alterra

Junk WJ, An S, Finlayson CM, Gopal B, Květ J, Mitchell SA, Mitsch WJ, Robarts RD (2013) Current state of knowledge regarding the world's wetlands and their future under global climate change: A synthesis. Aquatic Sciences 75:151-167

Kotze DC, Ellery WN, MacFarlane DM, Jewitt GPW (2012) A rapid assessment method for coupling anthropogenic stressors and wetland ecological condition. Ecological Indicators 13:284–293

LAI DYF (2009) Methane dynamics in northern peatlands: A review. Pedosphere 19:409-421

Lundegårdh H (1927) Carbon dioxide evolution of soil and crop growth. Soil Science, 23(6), 417-453

Maljanen M, Sigurdsson BD, Guömundsson J, Oskarsson H, Huttunen JT, Martikainen PJ (2010) Greenhouse gas balances of managed peatlands in the Nordic countries present knowledge and gaps. Biogeosciences 7:2711-2738

Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Synthesis. Island Press, Washington D.C

Mitsch WJ, Gosselink JG (2015) Wetlands. 5th edition. John Wiley & Sons, Inc., New Jersey

Moore TR, Knowles R (1989) The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Canadian Journal of Soil Science 69:33-38

Orange-Senqu River Commission (2018) Protecting the source of Lesotho's "White Gold":24. ORASECOM & Lesotho Department of Water Affairs. https://www.sadc.int/files/6215/3805/7503/EN_ORASECOM_Khubelu_Wetlands_Protection Case_Study-web.pdf

Senger DF, Saavedra Hortua DA, Engel S, Schnurawa M, Moosdorf N, Gillis LG (2021) Impacts of wetland dieback on carbon dynamics: A comparison between intact and degraded mangroves. Science of the Total Environment 753:141817. Elsevier B.V, Bremen

Ólafsdóttir R (2015) Carbon budget of a drained peatland in Western Iceland and initial effects of rewetting. Masters thesis, Agriculture University of Iceland, Reykjavik

Overpeck J, Garfin G, Jardine A, Busch DE, Cayan D, Dettinger M, Fleishman E, Gershunov A, MacDonald G, Redmond KT, Travis WR, Udall B (2013) Summary for decision makers. Assessment of climate change in the Southwest United States: A report prepared for the National Climate Assessment. Island Press, Washington D.C.

Parish, F Sirin, A Charman, D Joosten, H Minayeva, T Silvius, M and Stringer L (2008) Assessment on peatlands, biodiversity and climate change: Main report. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen

Ramsar Convention on wetlands (2018) Resolution XIII.12 Draft Resolution on guidance on identifying peatlands as Wetlands of International Importance (Ramsar Sites) for global climate change regulation as an additional argument to existing Ramsar criteria, United Arab Emirates, 21-29 October. Dubai

Rowell DL (1997) Soil Science: Methods and applications. Department of Soil Science, University of Reading, Harlow

Russi D, ten Brink P, Farmer A, Badura T, Coates D, Förster J, Kumar R, Davidson N (2013) The economics of ecosystems and biodiversity for water and wetlands. Institute for European Environmental Policy IEEP, London and Brussels; Ramsar Secretariat, Gland.

Senger DF, Saavedra Hortua DA, Engel S, Schnurawa M, Moosdorf N, Gillis LG (2021) Impacts of wetland dieback on carbon dynamics: A comparison between intact and degraded mangroves. Science of the Total Environment 753:141-817

Trettin CC, Labovitch L, Lerotholi S, Mercer E (2008) The peatlands of Lesotho – an important ecological and socio-econmic resource\r\n. After wise use-the future of peatlands 1:88–91

UNEP (2019) GEO-6 Healthy planet , Healthy people edited by Wetlands International, 2012. Waterbird Population Estimates, 5th Edition. Summary Report. Wetlands International, Wageningen, Netherlands

Wösten JHM, Ismail AB, Van Wijk ALM (1997) Peat subsidence and its practical implications: A case study in Malaysia. Geoderma 78:25–36

WWF (2016) Living planet report 2016. Risk and resilience in a new era. WWF International , Gland, Switzerland p. 32-33

Zedler JB, Kercher S (2005) Wetland resources: Status, trends, ecosystem services, and restorability. Annual review of Environment and Resources 30:39–74

Zhu Z (Ed (2010) A Method for assessing carbon stocks , carbon sequestration, and greenhouse-gas fluxes in ecosystems of the United States under present conditions and future scenarios Scientific Investigations Report 2010 – 5233. U.S. Geological Survey, Reston, Virginia