Assessment of the Carbon Pool at ProNamib Nature Reserve (PNNR)

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Thesis submitted in fulfillment/partial fulfillment of the requirements for the degree of Master of Natural Resources Management at the Namibia University of Science and Technology.

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Declaration

I, **Elizabeth Twitileni Pius**, hereby declare that the work contained in the thesis entitled: **Assessment of the carbon pool at ProNamib Nature Reserve (PNNR)** is my own original work and that I have not previously in its entirety or in part submitted to any university or higher education institution for the award of a qualification.

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List of Acronyms

CS	Carbon stock
DBH	Diameter at breast height
LOI	Loss-on ignition
MAWLR	Ministry of Agriculture, Water and Land Reform
NRNR	NamibRand Nature Reserve
PNNR	ProNamib Nature Reserve
SOC	Soil organic carbon
WB	Walkley black
BD	Bulk density
d	Soil depth
%C	Carbon concentration

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Dedication

This thesis is dedicated to my parents, Hilma Shitalangaho and Josef Pius for being the best parents in the world.

Abstract

Climate change in many African regions, including Namibia, is projected to get worse in the coming decennia. The consequences will mostly affect communities living in rural areas (especially in semi-arid and arid areas) as they depend on agriculture for livelihood. Poor land uses combined with drought, flood or low precipitation can eventually lead to hunger and a collapsed economy. But it is believed that global drylands have the potential to sequester carbon of about 1000 teragram (1000 Tg C yr^{-1}), if the dryland soil and biodiversity are restored. This study took place in the ProNamib Nature Reserve (PNNR) and neighbouring livestock farms (Eckberg and Houmoed). The area is semi-arid with localised rainfall. The study's objectives were to define the appropriate methods for determining the carbon stock in arid environments; to map and investigate the spatial pattern of the carbon stock at PNNR (ProNamib Nature Reserve) and compare that with the neighbouring livestock farm, and lastly; to investigate the key drivers of the carbon stock at PNNR and compare that with the neighbouring livestock farm. Carbon in drylands is found in different carbon pools, namely: vegetation (woody plants and herbaceous), soil and litter. We assessed carbon stock in three carbon pools (woody plants, herbaceous vegetation and soil). The study area was divided into three land management units, based on prior and current land uses (livestock farming abandoned in 2018, abandoned in 2000 and current livestock farming), and further stratified into habitats (river, mountain and grassplain). Data were collected using a stratified random sampling method in QGIS. Each management unit was allocated 30 sampling plots (ten per habitat), which totalled up to 90 sampling plots. The plots were 500m^2 in size for woody species, four one m^2 quadrats for herbaceous species and soil was collected at the centre of each plot up to a 30cm depth. Allometric equations were used to estimate the aboveground and belowground woody carbon stock. Herbaceous dry biomass was weighted, while the soil was analysed with the dry combustion/LOI method in the soil lab. These are among the methods that many researchers favour the most based on literature review. This study concluded that the soil carbon pool stores 90% of the carbon in the ProNamib area. The highest total carbon stock among habitats is recorded in the mountain (22 tonnes ha^{-1}). In terms of management units, the ''livestock'' unit has the highest carbon stock in the area (21 tonnes ha^{-1}), the second highest is recorded in the ''abandoned in 2018'' unit (18 tonnes ha^{-1}), while the lowest carbon stock in the area is found in the ''abandoned in 2000'' with 16 tonnes ha^{-1}. This study serves as a pilot study for long-term carbon monitoring projects in the arid areas of Namibia and as a carbon baseline in the ProNamib.

Keywords: Drylands, Carbon stock, Habitats, Management units, ProNamib Nature Reserve, Allometric equations

Chapter 1: General Introduction

1.1 Background

Global climate change is a major issue of this century and it is believed to be a consequence of anthropogenic impacts and natural irregularities (Alamgir and Al-Amin, 2008). Due to agricultural and industrial activities and deforestation, increasing levels of carbon dioxide and all other greenhouse gases (GHG) will remain a risk to the environment (Alamgir and Al-Amin, 2008; López-Santiago *et al.,* 2019; Wang *et al.,* 2014). In Africa, the climate is predicted to increase at about two times the global rate of temperature increase, and the environment is expected to become drier in the Southern African region (James & Washington, 2013; Archer *et al.,* 2018; Engelbrecht, 2019). In 2019, drought affected numerous African regions, especially those in Southern Africa such as Namibia, Botswana and western South Africa, the 2018 - 2019 rainy season was close to/below 50% average (WMO (World Meteorological Organization), 2020). These climate variabilities (reduced precipitation and warmer temperature) will negatively impact the environment as well as the economy, not just in Africa but globally (Engelbrecht, 2019; WMO (World Meteorological Organization), 2020).

The concern and awareness around the negative effects of greenhouse gases which are increasing at an alarming rate, led to the launch of the Kyoto Protocol, in 1997, by the United Nations Framework Convention on Climate Change (UNFCCC) (Gupta, 2011). From this protocol, carbon sequestration and the global carbon credit market were considered possible solutions to reduce the excessive release of greenhouse gases. Currently, carbon credit is the new carbon emission trading currency between businesses/organisations, created from the Kyoto Protocol as a strategy to control and lessen the effects of greenhouse gas emissions (Garg *et al.,* 2017; Link *et al.,* 2008).

Non-polluting businesses/organisations sell carbon credits, while polluters buy carbon credits (Gupta, 2011). One carbon credit is equivalent to one tonne of carbon dioxide to be released into the atmosphere, or any other greenhouse gas. Through this carbon trade market, global greenhouse gas emissions can be measured and help keep global carbon emissions at acceptable levels, as well as force companies/businesses to figure out more ecologically sustainable ways to conduct their businesses (Gupta, 2011). To access the global carbon credit market, businesses/organisations, have to choose a suitable registry from the existing carbon registries, such as the Plan vivo, Verra, Australia C Credit Union (ACCU), or California Action Climate Registry, to register their projects that are reducing GHG. Each project needs to be carried out based on the chosen registry's protocols as they vary per registry.

Drylands, in particular degraded drylands, offer large areas for afforestation, reforestation and any other means of land enhancement to enable an increase in carbon storage on land, even though they do not contribute much to the global carbon sink. They make up 47% of the earth's land surface and desertification is a serious concern in these areas (UNEP, 1992 as cited in Sharma *et al.,* 2012). Soil in drylands vary extensively, therefore suitable land management approaches that minimise soil disturbance are vital as they may lead to an increased soil carbon stock and simultaneously lead to carbon sequestration potential (Sharma *et al*., 2012).

The potential to sequester carbon in drylands can be enhanced through the restoration of degraded soils and proper land use strategies to prevent future land degradation ((Lal, 2001; Sharma *et al*., 2012). Due to the limited amount of water, dryland soils are usually considered low in carbon, however, through favourable land use/land management methods, productivity can be achieved consequently providing carbon sequestration potential (Farage *et al.,* 2007). Global drylands ecosystems have the potential to sequester carbon of about 1000 teragram (1000 Tg C yr^{-1}) (Lal, 2002). In some dryland areas, like Pakistan, there is potential to sequester carbon by using plant species that are adaptable to the area, such as woody plants that can adapt to soils with low moisture and high salinity (Hammad *et al.,* 2020).

In terms of land use and farm management in arid areas, researchers need to understand the current and previous land use approaches in order to determine their impacts on carbon storage as well as global carbon distribution and size. Different land uses and farm management are vital aspects that control carbon storage (Canadell, 2002; Guo and Gifford, 2002). Alterations in land use can cause a major carbon fluctuation or can lead to an increase or decrease in carbon stock due to a change in land cover (Canadell, 2002; Guo & Gifford, 2002). When the balance between the inflow and outflow of carbon in the soil is disturbed by land use change, which can either happen naturally or due to human activities, the soil could act as a carbon sink or source until a new equilibrium is established in the new ecosystem.

Guo & Gifford (2002) found that land use changes, such as from pasture to plantation, native forest to plantation and native forest to cropland, reduced soil carbon stock on average by 9% after they analysed 74 publications on land use changes, but they also stated that not all land use changes led to a decrease in soil carbon stock. The results are however biased, as most of the data is derived from only four countries (Australia, New Zealand, USA and Brazil) (Guo & Gifford, 2002; Petrokofsky *et al.,* 2012b). Other studies found that there was a significant difference in soil organic carbon in the top 40cm depth, according to different types of land use in drylands (Albaladejo *et al.,* 2013). In the upper layers 0-20cm and 20cm-40cm, both the forestland and shrubland showed a higher carbon stock compared to cropland. Shifting from shrub/forestland to cropland will reduce soil carbon stock, as it can increases soil erosion and reduces the amount of biomass, while the reverse typically leads to soil carbon gain (Albaladejo *et al.,* 2013; Boakye-Danquah *et al.,* 2014; Leifeld *et al.,* 2011).

The type of land management chosen will dictate whether carbon is being lost or gained (Boakye-Danquah *et al*., 2014; Sharma *et al*., 2012). Heavy grazing and fire practices in dry areas lead to carbon loss, as heavy grazing reduces litter accumulation and species composition, while fire exposes soil and allows the release of carbon back into the atmosphere as vegetation burns. Another land use practice, which is believed to contribute to carbon loss is tillage, as the process modifies the natural development of microbial activities thus assisting carbon release from the soil (Boakye-Danquah *et al*., 2014). Agroforestry is also one of the land management methods found to be effective in increasing carbon in semi-arid areas. However, it is only effective when suitable plant species are integrated into the process (Boakye-Danquah *et al*., 2014).

1.2 Problem Statement

When livestock farmers settled in the Southern pro-Namib in the 1950s, the land was sliced into pastures and fenced. Their fences adversely affected the migration routes of wildlife in the area (N. Odendaal, Personal Communication, June 2021). Many ungulate species and predators were hunted to local extinction and livestock competed for grazing with wildlife. Due to the area's harsh climate conditions which have been worsened by the recent drought in 2015/2016 and poor farming practices, the land has degraded. The challenging farming conditions and the economic impact of Covid-19 have created an opportunity to unify former livestock farmlands into one conservation unit to restore and conserve biodiversity.

It is assumed that restoring wildlife's ancient migration routes and biodiversity via re-wilding will improve the area's carbon pool, allowing significant carbon sequestration to take place which will potentially make the area eligible to earn carbon credits (Díaz *et al*., 2009; NamibRand East Nature Reserve, n.d.). To be eligible for earning carbon credits, it is necessary to determine a carbon baseline to determine if future management practices improve carbon stocks (Verified Carbon Standard, 2012). As drylands show high spatial and temporal variability in carbon exchange based on rainfall, topography, vegetation and we presume management, an assessment of this spatial and temporal variability is required. This study therefore aimed to produce a carbon baseline of the reserve in order to evaluate the spatial variability of carbon stocks. Future monitoring would be required to assess the temporal variability. The baseline with an assessment of its spatial and temporal variability is needed to determine the carbon credit potential and allow investors to purchase carbon offsets.

1.3 Research Objectives

1. Defining appropriate methods for determining the carbon stock in arid environments.
2. Map and investigate the spatial pattern of the carbon stock at PNNR (ProNamib Nature Reserve) and compare that with the neighbouring livestock farm.
3. Investigate the key drivers of the carbon stock at PNNR and compare that with the neighbouring livestock farm.

1.4 Research questions

1.1 What methods have been used for assessing carbon stock?

1.2 What are the carbon pools found in arid environments and which existing methods are suitable for assessing their carbon stock?

2.1 Which habitats store most of the carbon at PNNR?

2.2 Which habitats store most of the carbon at the neighbouring livestock farm?

3.1 How much carbon is stored above and belowground at PNNR and the neighbouring livestock farm?

Hypotheses

H01: All the existing carbon assessment methods are suitable for application at PNNR.

Ha1: Not all existing carbon assessment methods are suitable for application at PNNR.

H02: All carbon pools are the same.

Ha2: Carbon pools are significantly different for at least one habitat.

H03: The carbon stock at PNNR is not driven by historical farm management approaches.

Ha3: The carbon stock at PNNR is driven by historical farm management approaches.

This proposed study will take place in a dryland area with different prior land uses/management methods. It will focus on the assessment of above and belowground carbon as well as soil carbon. The results will determine the area's carbon sequestration potential and carbon credit eligibility.

1.5 Significance of the Study

The study serves as a pilot study for long-term carbon monitoring projects in the arid areas of Namibia. The results/output of the study will determine whether dry areas, such as ProNamib Nature Reserve, have the potential to sequester carbon and are eligible for carbon credits. It also provides reliable data for carbon stock in Namibia, consequently, serving as a reference for further carbon studies in terms of acquiring carbon credits in dry areas. The study also contributes to climate change combat through its contribution to the body of carbon knowledge in arid lands.

1.6 Delimitations of the Study

Sampling plots in the livestock area had to be moved/reallocated into one livestock area as it was not possible to sample in one of the selected livestock farms due to some unforeseen circumstances. The timing of data collection (herbaceous) was off a bit, as the grasses and herbs were already dry or half dry towards the end of May 2022. Harvesting/destructive sampling of woody species was not possible, I had to use proxies for wood densities of woody species I could not find in the literature.

Chapter 2: Literature Review

Terrestrial carbon stock can be measured in five different ecosystems: aboveground, belowground, deadwood, litter, and soil (Issa *et al.* 2020). Aboveground carbon refers to the vegetation biomass (trees, shrubs, grass and herbs), while belowground carbon refers to the roots. Both the above and belowground carbon stock is influenced by various factors (Meena *et al.* 2019): Vegetation structure, rainfall, temperature, topography, vegetation composition and species diversity, human activities and land use changes. Therefore, it is vital to establish the existing carbon pools in different land cover types for better management approaches for carbon sequestration and storage.

Tree density and size can influence the carbon stock as trees with increasing diameter at breast height tend to increase biomass and store more carbon (Meena *et al.,* 2019). Several studies found that tree carbon stock is regulated by stand features and anthropogenic disturbances, while climate and soil properties are the driving factors of soil carbon stock (Wiesmeier *et al.,* 2019; Wu *et al.,* 2022; Saimun *et al.,* 2021).

Grasslands contain at least 10% of the global soil carbon stock and many countries depend on these grassland resources (Ghosh and Mahanta, 2014). Both tropical and temperate natural grasslands play a significant role in the carbon cycle. Wang *et al*. (2014) found that an increase in annual precipitation and soil moisture improves plant production which in return increases the soil organic carbon density in desert grasslands. Sequestration in grasslands can be improved through several management practices such as sowing favourable fodder that is adaptable to the environment, grazing management, irrigation, applying fertilizers and restoring grasslands that are degraded (Ghosh & Mahanta, 2014). It is estimated that 0.2 to 0.8 gigatonnes (Gt) carbon dioxide, through land restoration practices, can be sequestered in grasslands soils globally by 2030 (Ghosh & Mahanta, 2014).

2.1 Soil carbon pool

Global drylands comprise 241 pentagrams (Pg) of soil organic carbon and they have a big impact on the global carbon cycle because of their massive area (Lal, 2004). These areas are prone to degradation and desertification which can result in high carbon dioxide emissions into the atmosphere. Many soil types exist in drylands, and the physical and chemical properties of these soils differ extensively. Some soils are unable to hold water and nutrients and they have low soil organic carbon. Desertification in these areas is common because of rainfall anomalies, wind and differences in surface temperatures (Lal, 2004). These environmental factors affect the vegetation cover, creating highly variable vegetation cover with large areas of bare ground between vegetation which in turn influence the density of soil organic carbon.

Soils are considered to be the major pool of the terrestrial carbon cycle (Petrokofsky *et al*., 2012a). The soil environment is where biotic and abiotic components interact (Sharma *et al*., 2012). The interaction regulates the flow of materials to and from the atmosphere, pedosphere and hydrosphere. It is known that the soil is an essential part of the climate change solution, although it can also be a problem due to poor land use change decisions and different land management practices. Knowledge and understanding of the carbon cycle in the soil is essential. We need to understand the distribution patterns of the soil organic carbon and the driving factors of these patterns as they will guide us to determine/find suitable strategies for land use/land management (Albaladejo *et al*., 2013; Wang *et al*., 2014). Mean annual precipitation, temperature, microbial abundance, the amount of biomass, land use and land management are the factors that determine the balance between carbon loss and gain.

Researchers found that there is sufficient evidence that the factors regulating the carbon dynamics of the topsoil and subsoil are different, however, the topic has not been investigated much (Albaladejo et al., 2013; Salomé *et al.,* 2010). The topsoil is more prone to drought and nutrient inputs and temperature upsurge compared to the subsoil (Fierer *et al.,* 2003; Salomé *et al*., 2010). On the other hand, carbon turnover models tend to assume that the factors regulating the topsoil and subsoil are similar, despite the observations indicating the microbial biomass and activity that decreases with the soil depth (Jenkinson and Coleman, 2008; Salomé *et al*., 2010). In addition, Gaucher *et al*. (2015) & Iais *et al.* (2011) stated that soil organic content is influenced by depth. It is higher in the upper soil layers and decreases as the depth increases but then again, the relationship between soil organic content and soil depth can differ due to anthropogenic activities. Cropping is one of the human activities that can change soil organic content, as well as tillage which can reduce organic matter in the topsoil depending on the tillage intensity.

2.2 Existing carbon stock methods and analysis

There are two types of field assessment methods that many researchers have used to determine above and belowground biomass; destructive and non-destructive methods (Vashum, 2012). These methods enable us to determine the amount of carbon the vegetation and soil in that specific area can sequester. In cases of land clearing or fire, these methods simultaneously determine the amount of carbon dioxide that can/would be released/emitted into the atmosphere.

The destructive method involves the harvest, weighting and oven drying of trees, shrubs, grasses and herb samples that are collected (Vashum, 2012). This method is most direct and accurate for assessing vegetation in a specific area and researchers use it to genera site-specific allometric models. However, it is time consuming, labour intensive and costly. It is unrealistic in degraded areas with endangered species that cannot be harvested. The non-destructive method does not involve any harvest of vegetation. To estimate the biomass and carbon stock, physical measurements of trees/shrubs are taken (the diameter at breast height, the height, volume and wood density), after which existing allometric models are applied. This method is less accurate but it is practical in areas with endangered or rare plant species that are protected from harvesting.

Vegetation biomass is estimated with allometric models using the diameter at breast height (DBH) and height (H) (Chave *et al.,* 2014; De Cauwer *et al.,* 2020). These allometric equations can either be site-specific, species-specific or general allometric equations. The allometric models should be carefully chosen depending on the type of vegetation (Brown *et al.,* 1989; Chave *et al.,* 2005; Lima *et al.,* 2012), as most of them are less applicable to arid areas (Issa *et al*., 2020). Researchers have stated that local/site-specific allometric models based on the tree population of the study area, will predict more accurate estimates of the forest/woodland biomass since they consider site conditions (Brown *et al*., 1989; Kim *et al.,* 2011; Vashum, 2012).

Many soil carbon studies used the same method to collect soil samples, however, the intervals/layers and depths at which samples are collected differ. Some soil samples are collected to a depth of 30cm (Daryanto *et al.,* 2013; López-Santiago *et al*., 2019; Nijbroek *et al.,* 2018), at 50cm (Mills *et al.,* 2005), while others collected soil samples as deep as 100cm (Yang *et al*., 2014) and 102cm (Mills and Cowling, 2010). Based on the literature, the most common soil depth used for soil organic carbon is 100cm and 30cm. It is advised to measure the soil carbon to a depth of at least 30cm, as soil carbon pool variations are likely to be visible at this depth (IPCC, 2003). Measuring and monitoring soil carbon beyond 30cm can be costly, however, it is recommended for projects measuring plants with deep roots.

Soil analysis is done using the two most common lab methods, either the Walkley Black (WB) or the Dry combustion/Loss-on ignition (LOI) method. LOI is less labour intensive and less expensive compared to other methods such as the Walkley Black method. Wang *et al.* (2013) found that, though LOI method has not been widely used in semi-arid and arid soil, the method is reliable and that it could provide accurate results for dryland soils. WB is more reliable is areas with high clay content and calcareous, while LOI is more suitable in soils with a high soil organic matter and low clay content (Ali, 2021).

Furthermore, the integration of geospatial technologies such as remote sensing and GIS with field-based measurements, has shown to be cost-effective and reliable, especially over large or inaccessible areas (Issa *et al*., 2020). These tools are frequently used to upscale the field-based methods. These technologies make field assessments less challenging in areas with complex stand structures, fluctuating environmental conditions and sparsely vegetated areas (which is common in drylands) (Issa *et al*., 2020).

Chapter 3: Methodology

3.1 Study area

The study took place in the newly established ProNamib Nature Reserve (PNNR) and neighbouring livestock farms (Eckberg and Houmoed) (Figure 2). The reserve is located about 100km west of Maltahöhe, Hardap Region. The PNNR is a sister reserve to the old NamibRand Nature Reserve (NRNR). It is situated in the pro-Namib Desert between the existing NRNR and the higher-rainfall escarpment area. The Great Western Escarpment only spreads as far as the south-eastern corner of the PNNR and the area is scattered with inselbergs (Burke, 2022). The area was a livestock farming zone in the past before it was converted to a nature reserve in 2021. It harbours a variety of habitats such as large grass plains, red sand dunes and granite inselbergs (NamibRand Nature Reserve Guidebook, 2017,).

It has an arid to hyper-arid climate with localised rainfall. In the PNNR, the weather stations are grouped closely, but distribution still vary greatly. The highest rainfall over the two-year period (2021-2022) was recorded at the Suidekruis house (200mm) in the southern part of Pro-Namib, the lowest at the Stukkend Dam in the West of the Reserve (10mm) (Burke, 2022). Overall rainfall was higher in 2022, with five stations receiving over 100mm, while only three received that much in 2021. More on the area's rainfall longterm pattern, this arid areas's rainfall is highly variable between years (Figure 1), with a mean annual precipitation of 88 mm , and it influences the area's vegetation dynamics. The area's rainfall is low on the west side of the area and it increases towards the eastern escarpment. Annual average temperature ranges from 18° to 21°C. The PNNR is an amalgamation of six farms (Nubib, Vrede, Suidekruis, Waterkop, Erfstuk and Eldorado) which add up to a total area of 48 027 hectares.

The farms had different previous owners, hence different management histories; Waterkop and Erfstuk had no livestock for the past 20 years; Suidekruis had no livestock since 2000, similar to Vrede, however around 2020 Suidekruis introduced about 6 sheep and 5 cattle while Vrede had approximately 20 cattle; Nubib had about 300 sheep before 2012, and 150 cattle and 600 sheep from 2012 to 2018, Eldorado is currently farming with 102 sheep, 56 cows and 80 cattle. The neighbouring livestock farms (Eckberg and Houmoed) are currently farming with livestock (350 cattle, 5 horses and 300 sheep combined). The farm's landscape covers comparable habitats to PNNR (riverbeds, grasslands and rocky/mountainous areas, including granite inselbergs).

The vegetation ranges from grass plains to sparse shrublands. Arid and semi-arid areas appear to support different annual plant species depending on the amount of rainfall as well as the intervals between the rainfall events (Noy-Meir, 1973; Beatley, 1969 as cited in Burke, 2022). Common woody species found in the area consists of species such as trumpet-thorn tree (*Catophractes alexandri)*, *Commiphora spp.*, *Acacia* species such as camel thorn tree *Acacia* (*Vachellia*) *erioloba,* mountain thorn *(Acacia (Senegalia) hereroensis),* sweet thorn (*Acacia* (*Vachellia) karoo),* black thorn (*Acacia (Senegalia) mellifera)* and candle-pod *(Acacia (Senegalia) hebeclada* subsp*. hebeclada).,* shepherd's tree (*Boscia albitrunca)* and smelly shepherd's tree (*Boscia foetida)*, *Ficus spp.* and *Grewia spp.* (Braine, 2021). Grass species comprise Kalahari sand quick grass (*Schmidtia pappophoroides)*, bushman grass (*Stipagrostis uniplumis* var. *uniplumis)*, ring windgrass (*Eragrostis annulata)* and natal grass (*Melinis repens* subsp. *repens)*.

In terms of fauna, ungulate species like the greater kudu (*Tragelaphus strepsicerus)*, oryx (*Oryx gazelle)*, springbok (*Antidorcus marsupialis)*, steenbok (*Rhaphicerus campestris)* and common warthogs (*Phacochoerus africanus)* are also found in the area as well as burrowing type animals like yellow mongoose (*Cynictus penicillata*), common ground squirrel (*Xerus inaurus*) and bat eared fox (*Otocyon megalotis*). Predators such as black-backed jackal (*Canis mesomelas)*, African wildcat (*Felis Sylvestris lybica),* leopard (*Panthera pardus*) and spotted hyena (*Crocuta crocuta)*.

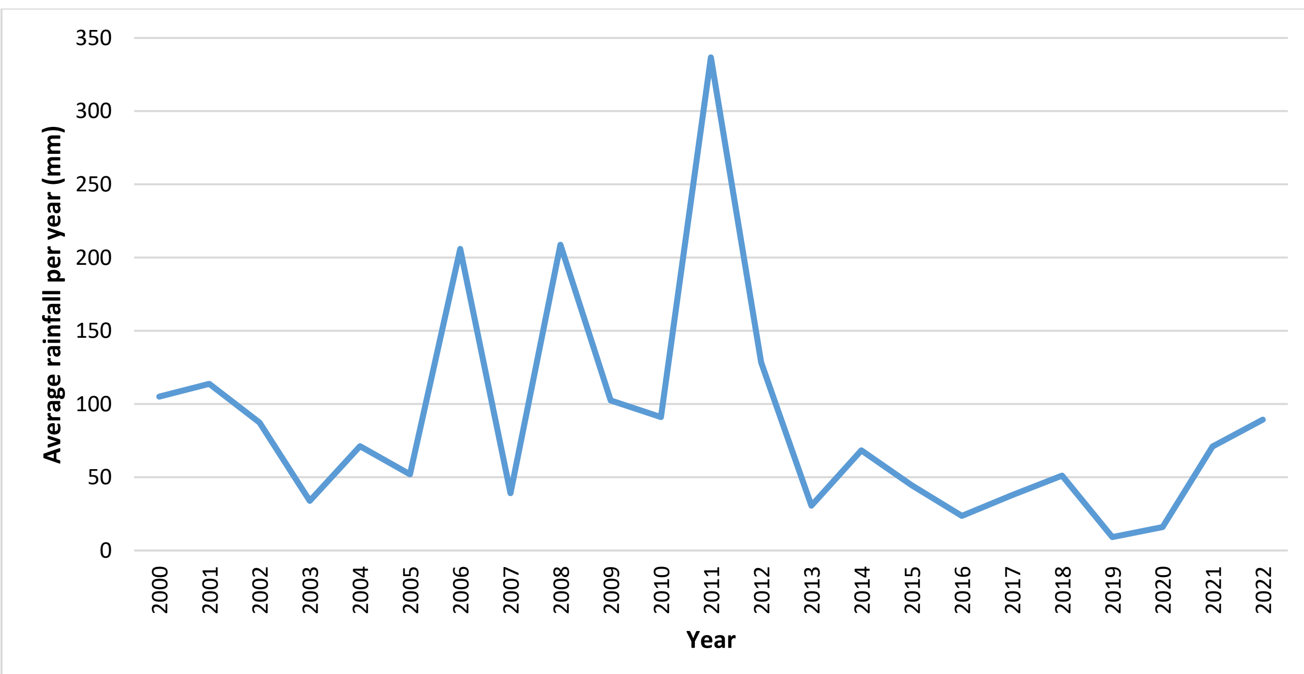

Figure 1 Long term average rainfall in the neighbourhood (NamibRand Nature Reserve) west side of the study area, 2000 to 2022.

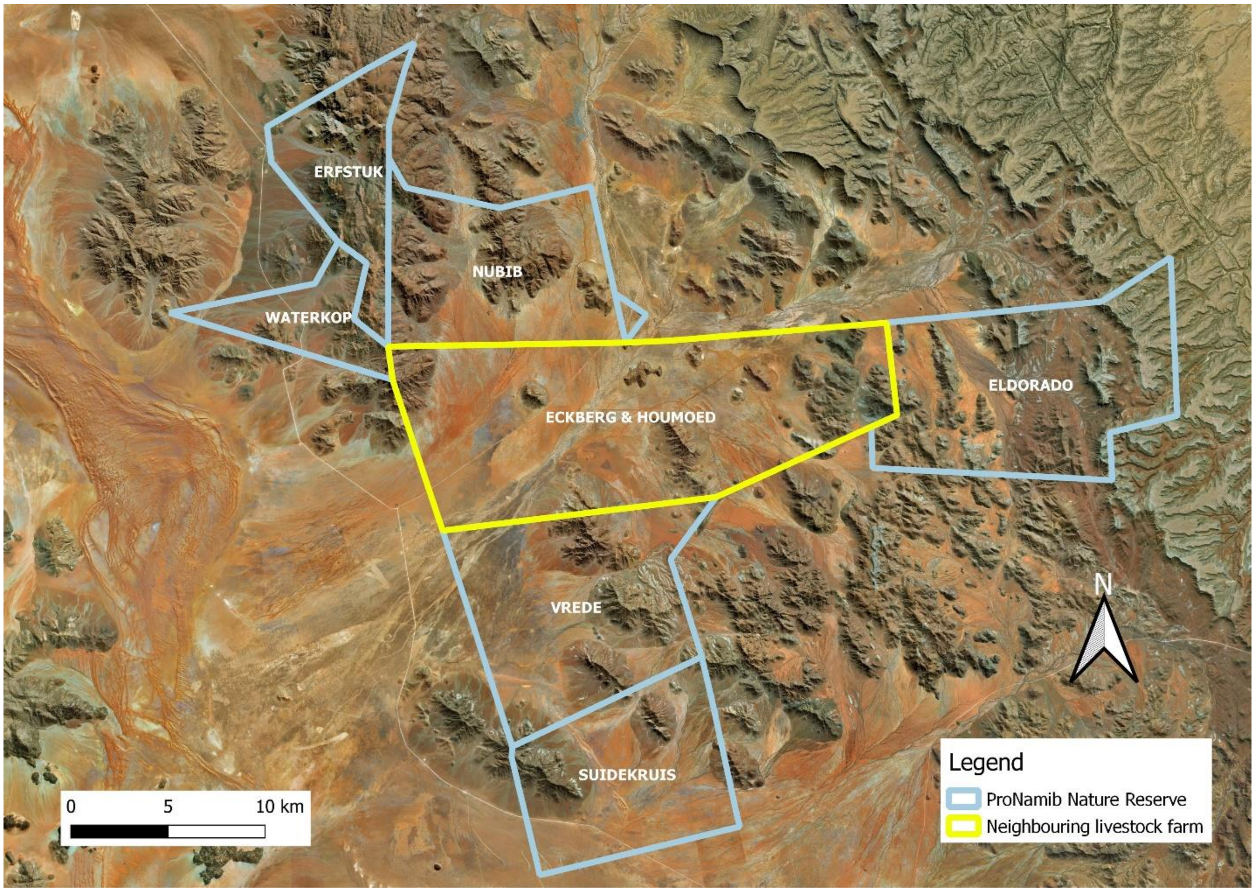

Figure 2 The study area (ProNamib Nature Reserve), including the neighbouring livestock farms (Eckberg and Houmoed).

3.2 Data collection

3.2.1 Defining appropriate methods for determining the carbon stock in arid environments.

Numerous methods have been developed for measuring carbon stock in different environments including arid areas. A literature survey was conducted, with the assistance of several scholarly search engines/databases such as Google Scholar, Science Direct and WorldWideScience.org, to search for published studies/ journal articles on carbon assessments. The survey was not limited to a timeline. The search criteria focused on scientific papers that looked at different carbon assessment methods in dry environments. To discover published studies, search terms such as carbon assessment; above and belowground carbon; methods to assess carbon stock were applied. In addition to the literature search, two suitable registry schemes from existing registries were chosen and their methods of carbon assessment were compared to the scientific literature. The Verra/VCS registry (VM0021 protocol Soil carbon quantification methodology) and the Australian registry scheme were selected, as their methods appeared to be the most suitable for the project.

3.2.2 Map and investigate the spatial pattern of the carbon stock at PNNR and compare with the neighbouring livestock farm. Investigate the key drivers of the carbon stock at PNNR and compare with the neighbouring livestock farm.

Study design

For mapping and determining carbon stock, the study area was stratified into three management units based on prior and current management: (a) abandoned livestock area in 2000, then grazed with low intensity from 2020 onwards (b) recently abandoned livestock area in 2018 and (c) current livestock farms, which included the neighbouring farms (Eckberg and Houmoed) and Eldorado farm (Figure 3). Further stratification was based on ecosystem criteria, where each management unit was further stratified in three different habitats (mountain, grassplain and river) (Figure 4). Stratification of the study area was performed in QGIS, using a visual interpretation of Bing aerial images available in QGIS.

Ten plots were allocated per habitat in each management unit through a stratified random sampling method, which then totalled 90 plots overall. Note that the livestock unit plots did not include Eldorado farm due to unanticipated circumstances (Figure 5). Plots were circular with a 12.62m radius ($500m^2$) (Macdicken, 2015). The centre of each plot was located with a handheld Global Positioning System (GPS) in the field (Knox and Grunwald, 2018). To optimise the accuracy, waypoint averaging was used for each plot. Recording sheets (Appendix 1) and field equipment were prepared before data collection and all the necessary plot details were recorded on the recording sheet before sampling.

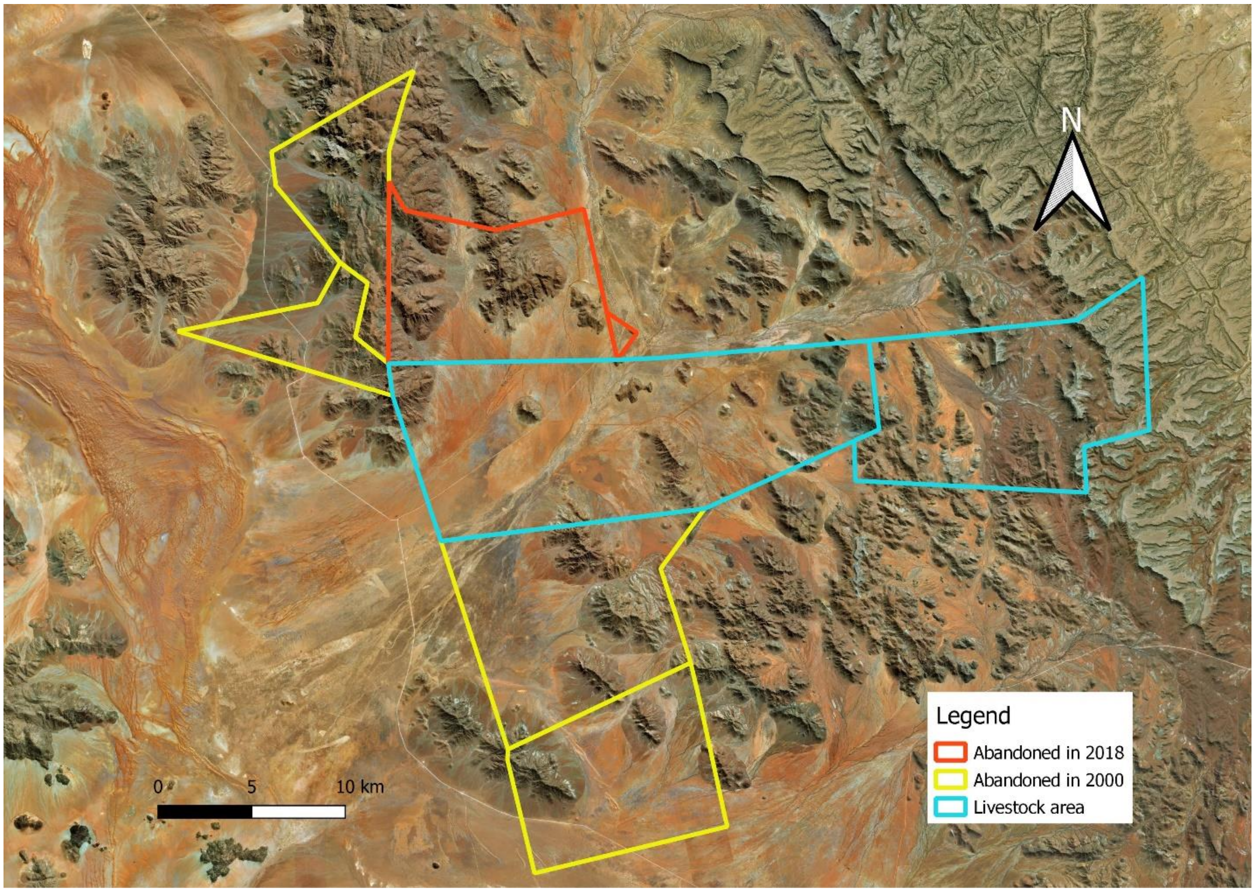

Figure 3 The three management units based on their management histories

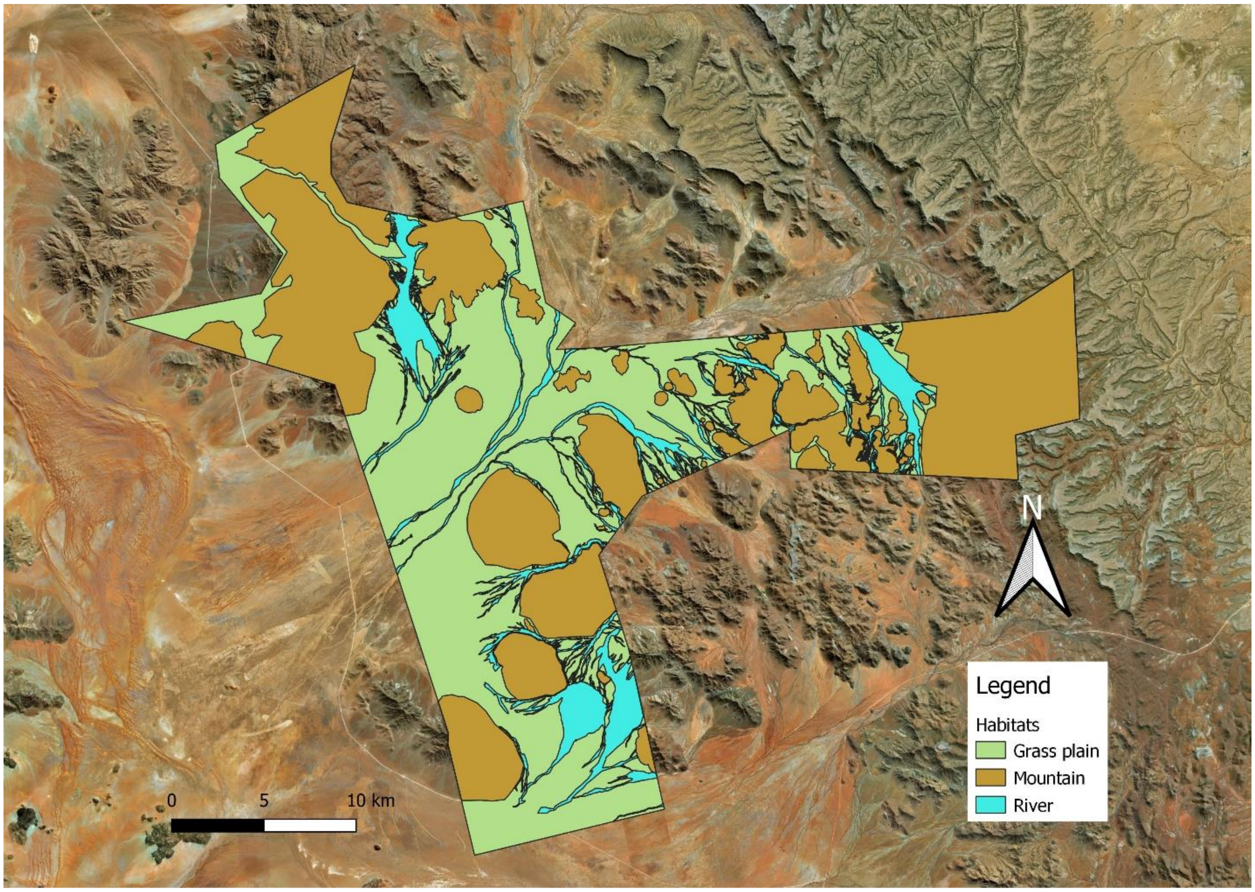

Figure 4 Habitats within the management units (grass plain, mountain and river)

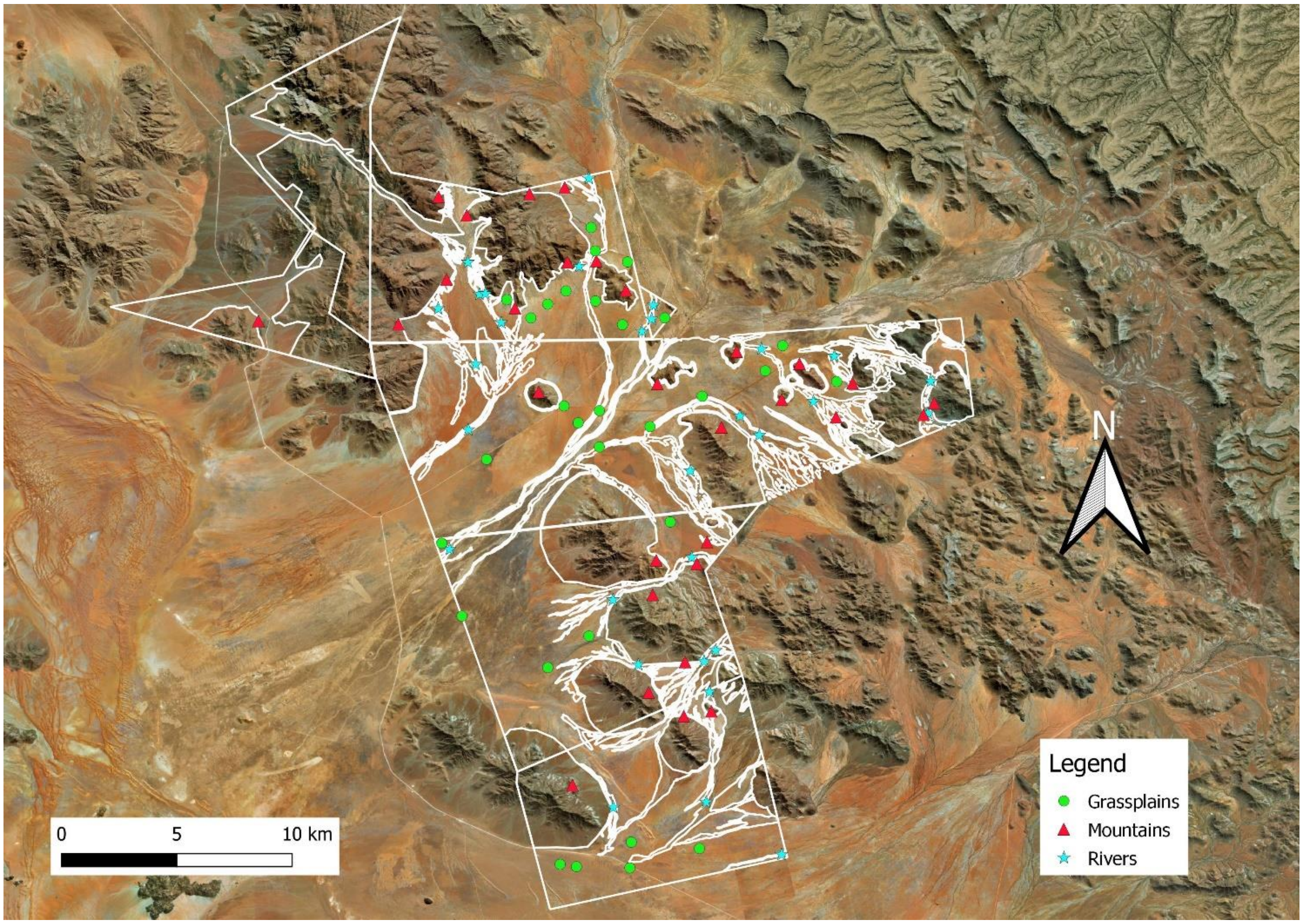

Figure 5 The 90 permanent sample plots where samples were collected.

Vegetation sampling

Two methods were used to determine aboveground and belowground carbon stock, a destructive and non-destructive method. Field guides were used to identify trees, shrubs, herbs and grass to a species level within each plot. For those that couldn't be identified in the field, a sample was collected and a photograph was taken to be identified late (Figure 6 and Figure 7).

Figure 6 A – A species that could not be identified in the field. B - A compass that was used for directions. C - Measuring pole, measuring tapes. pencil and a book with recording sheets. D - Different textbooks used for identification.

Figure 7 Left - Entering the necessary data in the GPS. Right - some species samples collected for identification after fieldwork.

Woody species (trees and shrubs)

Aboveground biomass - all woody species within the 12.62m radius plot with a minimum height of 50cm were identified to a species level and assessed. The height was measured with a measuring pole except for the bigger/taller trees where a clinometer was used as the pole was too short. The stem height was measured as the distance between the first branch and the ground level, while the tree height is measured as the distance between the ground and the top of the tree (Husch *et al*., 1982; Husch *et al*., 2003 as cited in Moses 2013). Canopy was measured in two directions with a measuring tape or pole (north-south and east-west) to avoid bias (Tietema, 1993) (Figure 8). The stem basal diameter, if accessible at 30cm from the ground was taken with a measuring tape, as well as the stem diameter at breast height (1.3m, DBH) of woody species within the plot. For trees and large shrubs, the stem basal diameter and the DBH were easy to measure, while as for multi-stemmed species, it was a difficult and not possible to measure the stem basal diameter and DBH of the multitude of stems and their heights were mostly below 1.3m. Azimuth and distance from the plot centre as well as the phenology of each shrub/tree were recorded. The number of stems below 30cm in height was also recorded. For woody plants with irregular trunks or deformities, measurements were taken above the abnormalities (Chave *et al.* 2014). For belowground biomass, two *Rhigozium* shubs from different height levels were harvested to test measuring their root biomass (Figure 8).

Figure 8 Left - Measuring the canopy width with a measuring pole. Right – Rhigozium shrub roots

Herbaceous species (grass and herbs)

A 1m × 1m quadrat was placed at a 5m distance from the plot centre in all four directions of the plot, clockwise (north-east-south-west) (Figure 9). All herbaceous species (and woody species below 50cm height) within the quadrat were identified to a species level, the species diversity, as well as the overall percentage cover of vegetation within the quadrat observed from above. All herbaceous plants were clipped close to the ground with secateurs and placed in marked brown paper bags and transported back to the farm office/lab for fresh biomass weighing. All the paper bags were labelled with the date, plot number, management unit and habitat before placing the samples inside.

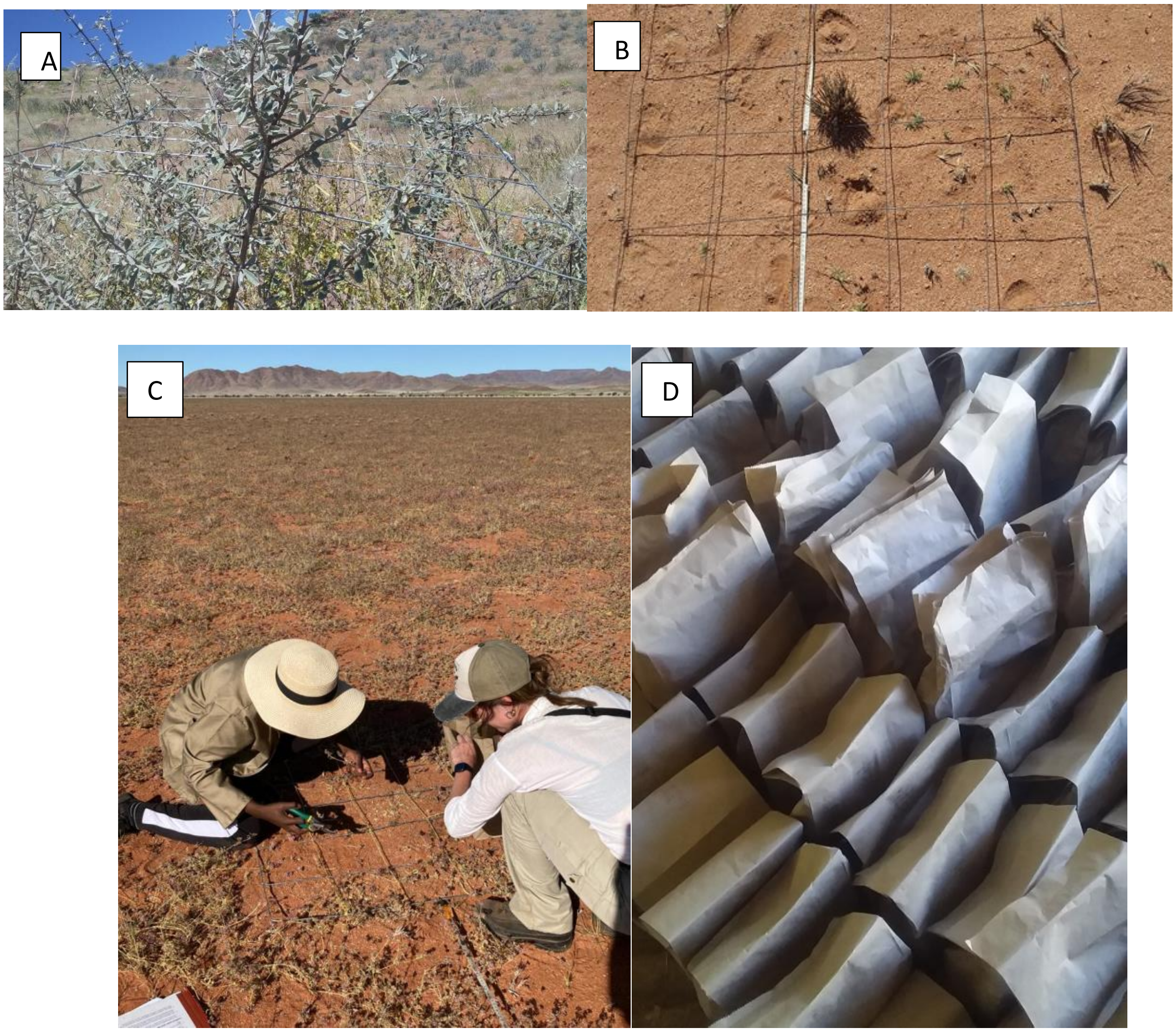

Figure 9 A- The quadrat spot landed on top of a woody species. B- A bare grassland plot. C- A grassland plot in the livestock area dominated by the herb Gisekia africana*. D- Papers bags that were used to store samples*

Soil organic carbon (SOC)

Before soil samples were collected, the top litter was removed/cleared (Mills & Cowling, 2010; Nghalipo *et al*., 2019; Shifa, 2017). Soil samples were collected from the centre of each plot with a small spade at a 30cm depth, but due to the rocky terrain, this was not possible for plots in the mountain area. Twenty-eight oil samples in the mountain areas were collected at a depth of 20cm and below, one was at 23cm, and only one went to a 30cm depth. The lowest/shallowest was 5cm deep in the ‘’abandoned in 2018’’ unit. Soil type was also recorded per plot (Figure 10). The samples were kept in brown paper bags and air-dried before transportation to the lab.

Figure 10 Soil type was determined with the water technique. A- Sandy-clay soil. B- Sandy soil.

3.3 Data analysis

3.3.1 Defining appropriate methods for determining the carbon stock in arid environments.

To determine suitable methods for assessing carbon stock in arid environments, all compiled papers were analysed based on ecological criteria (rainfall, habitats, carbon pools), management history, analysis and study design. The scientific literature was also compared to the methods of the Verra and the Australian carbon registry schemes. The potential carbon pools were identified from the assembled papers and the existing methods/approaches used were evaluated for transferability to this study. All the methods were critically examined, especially for soil and vegetation (above and below), as this study is focused on soil and vegetation carbon value. The methods that are not suitable for arid areas were removed and it was explained why they will not work, and vice versa.

In total 32 articles were compiled that assess carbon stock in dry areas. Two of the articles didn't match the criteria, while 16 papers didn't match the dry area rainfall pattern. Their annual rainfall was above 500mm, which is well above the ProNamib annual rainfall range. The remaining 14 papers were for areas with mean annual rainfall values similar to the study area, plus the two carbon registry schemes.

3.3.2 Map and investigate the spatial pattern of the carbon stock Investigate the key drivers of the carbon stock at PNNR and compare that with the neighbouring livestock farm.

Woody species (trees and shrubs)

Woody data were first entered, rearranged into a suitable format and cleaned in a spreadsheet. Data were analysed with established generic allometric models from Chave *et al*. (2014) to determine aboveground biomass. The Chave *et al.* (2014) model is appropriate if the DBH can be accurately measured in the field as it has been proven to be suitable for carbon stock assessment in many areas of the tropics, including Namibia (Abere *et al.,* 2017; De Cauwer *et al.,* 2020). We also used model1 of Conti *et al.* (2019) and compared how it performed compared to the Chave *et al*. (2014) model. The Chave model works best for tall and large woody species with easy-to-measure basal diameter and DBH such as *Acacia* species*, Boscia foetida, Boscia albitrunca, Adenolobus garipensis* and *Moringa ovalifolia*. For multi-stemmed woody species, model4 of Conti *et al.* (2019) was used to get the aboveground biomass. It is best suited for multi-stemmed woody species for which the basal diameter was impossible to attain in the field, as it only needs canopy diameter and height to estimate biomass.

Chave AGBest = $0.0673\ (\rho \times DBH^2 \times H)^{0.976}$

Model1 AGBest = $\exp\ (-2.281 + 1.525 \ln (BD) + 0.831 \ln (CD) + 0.523 \ln (H))$

Model4 AGBest = $\exp\ (-0.370 + 1.903 \ln (CD) + 0.652 \ln (H))$ *1.403

Where, ρ = wood density (g/cm^3), DBH = diameter at breast height (cm), BD = basal diameter (cm), CD = canopy diameter (m) and H = height (m) per individual woody species.

Wood density data were obtained from the Global Wood Density Database and for the species' wood density we couldn't find, proxies were used (Table 1). For *Boscia foetida* and *Boscia albitrunca,* the wood density of *Boscia salicifolia* was used as a proxy, while the woody density of *Commiphora marlothii* was used as a proxy for *Commiphora glaucescens* and *Commiphora tenuipetiolata*. The wood density of *Moringa ovalifolia* was used as a proxy for that of *Moringa oleifera*, and for *Adenolobus garipensis* the average wood density for African trees was used as no proxy could be found for it. According to literature, an average value of a known species of the family should be used if no wood density is available, or the average wood density of trees documented in Africa, which ranges between 0.58 and 0.67 g/cm^3 (Henry *et al.,* 2010 as cited in Abere *et al.,* 2017).

Table 1 Woody densities used to determine woody biomass per species (Global Wood Density Database)

ProNamib woody species	**Wood density (g/cm³)**	**Proxy used**
Boscia foetida	0.594	*Boscia salicifolia*
Boscia albitrunca	0.594	*Boscia salicifolia*
Commiphora glaucescens	0.456	*Commiphora marlothii*
Commiphora tenuipetiolata	0.456	*Commiphora marlothii*
Acacia erioloba	1.059	*NA*
Acacia mellifera	0.947	*NA*
Moringa ovalifolia	0.7	*Moringa oleifera*
Adenolobus garipensis	0.58	*African average woody density*

To convert aboveground biomass to carbon stock densities, the total biomass was multiplied by the IPCC (2006) default carbon fraction of 0.47 (IPCC, 2006, Pellikka *et al.,* 2018).

For belowground biomass, a root-to-shoot ratio was used via the MacDicken (1997) (Atsbha *et al.,* 2019) equation:

BGB = AGB × 0.2

Where: BGB is below-ground biomass, AGB is above-ground biomass and 0.2 is the conversion factor (or 20% of AGB).

Herbaceous species (grass and herbs)

Each bag with a herbaceous sample was weighed on a 0.1g accuracy scale immediately after collection and kept in brown paper bags for air drying (Figure 11). Samples were re-weighed until the dry weight stabilized. Both the wet and dry weights were recorded and the constant dry weight was considered the total biomass per quadrat. The average biomass of all four quadrats converted to the total plot size of 500m² is the total biomass per plot. The carbon content for herbaceous samples was calculated by multiplying the total dry biomass per plot with the IPCC (2006) default carbon fraction of 0.47. The portion of herbaceous cover per plot was the average of the four quadrats in each plot.

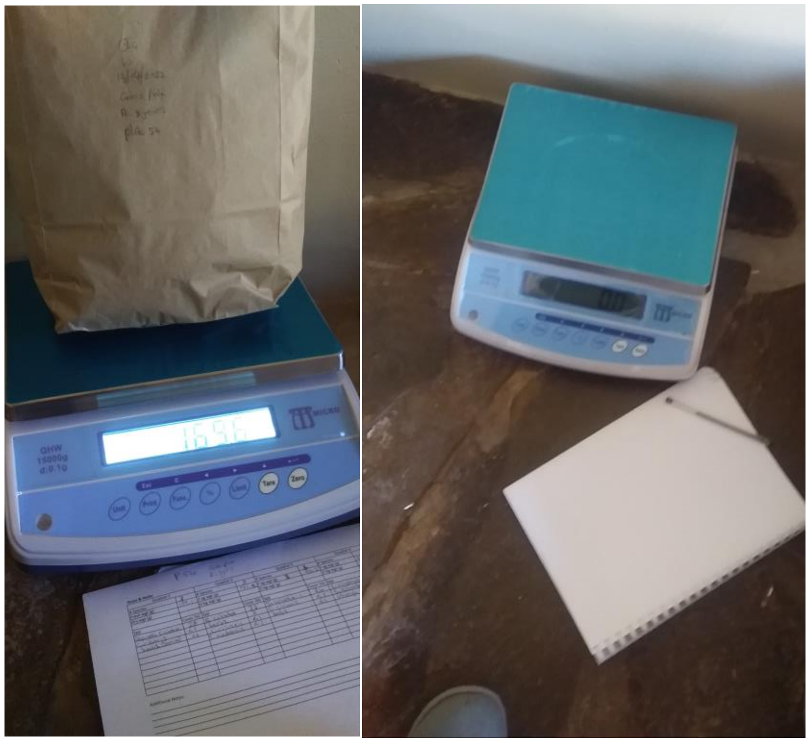

Figure 11 Left - Herbaceous sample bag being weighed. Right- The 0.1g accuracy scale that was used to measure herbaceous samples.

Soil organic carbon (SOC)

Soil samples were analysed at the Ministry of Agriculture, Water and Land Reform's (MAWLR) soil lab. The soil sample was mixed well in a small silver aluminium bowl before sieving. Half of each soil sample was sieved through a 2 mm sieve and stored in a small container for the analysis of soil organic carbon (Figure 12). The remaining half of the 90 samples were analysed with the Loss-on ignition method (Figure 13), and ten replicas were analysed with the Walkley-Black method (Figure 14) which added up to a total of 100 soil samples (90 + 10 replicas).

Loss-on ignition method: First, the empty crucibles were weighed, and then 10 grams of sieved soil sample was added with a spoon-like object into the crucible while still on the scale. The samples were dried by placing the crucibles in the oven at 105ºC overnight. In the morning, samples were removed from the oven and placed in the desiccator, cooled and then reweighed. The dry-weighted samples were placed into a muffle furnace and heated for six hours at 360ºC. After six hours the furnace was turned off to let the samples cool off overnight. The next day, samples were placed into the desiccator again, cooled and reweighed for the last time. The data was entered in the computer and it calculated the organic percentage.

Walkley-Black method: A dry 300 mg soil sample was weighed in a test tube. 1m Potassium dichromate was added to each tube, then 2 ml of sulphuric acid was added carefully and the content mixed well. Test tubes were heated at 80°C for 60 minutes. Samples were allowed to cool then 7ml water was added to each test tube/sample and mixed well. Samples were left overnight in the refrigerator to cool and settle. The cooled liquid sample was pipetted and the absorbance was read using a spectrophotometer the next day.

Soil bulk density (BD) was analysed from the sieved samples using the dry method. The following formula was used:

BD = M/V, where BD is bulk density, M is the weight of the container with the dried soil sample and V is the volume of the container.

The coarse fraction was not determined for the samples, thus soil carbon stock was analysed using this equation (Subedi *et al.,* 2010):

$SOC = BD \times d \ \times \%C.$

With:

SOC = soil organic carbon stock per unit area [t ha^{-1}],
BD = soil bulk density [g cm^{-3}],
d = the total depth at which the sample was taken [cm], and
$\%C$ = carbon concentration [%].

Figure 12 Top- Soil samples in containers after being sieved. Bottom- Soil was mixed well in the silver aluminium plate and then sieved with the 2mm sieve.

Figure 13 The Loss-on ignition method. Top left- Soil samples in crucibles before being placed in an oven. Top right- Soil sample was weighed after being removed from the oven. Bottom- Crucibles placed in a muffle furnace.

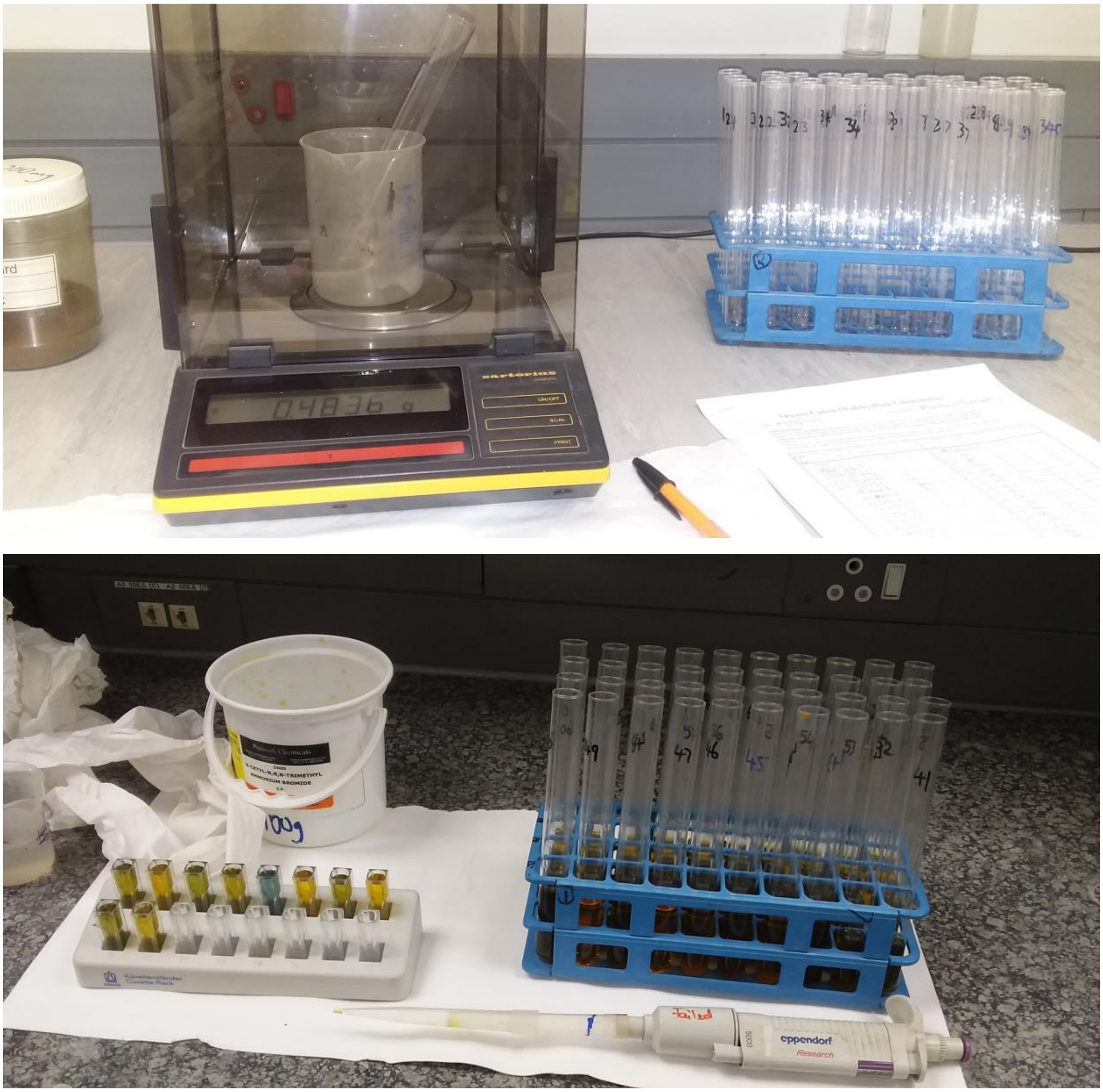

Figure 14 Walkley-Black method. Top- soil samples weighed in test tubes. Bottom- Pipetting soil samples in progress.

Statistical analysis

The residuals for all carbon pools were not normally distributed. The response variable (carbon values) were log-transformed to obtain a normal distribution, and a linear regression model was used to test the association between the management units and habitats. The structure of the models was as follows: LN(Number), where number is the value for which you want to find the logarithm. A natural logarithm was used in a spreadsheet.

The statistical tests were performed in R software. The allometric equations for woody species and graphs were applied in a spreadsheet. For Woody species, the carbon values were summed up per plot then converted to hectares, while for soil and herbaceous species, carbon sample values were converted straight to hectares. The total carbon stock for each carbon pool were obtained by multiplying area with value per hectare and then summed to find the total carbon stock stored. The overall aboveground carbon stock includes herbaceous and woody species combined, while the belowground carbon stock comprises of the woody belowground (roots) carbon. Soil organic cabon is separate.

Chapter 4: Results

4.1 Defining appropriate methods for determining the carbon stock in arid environments.

Table 2 shows that the existing methods for carbon analysis in dry areas are both destructive and non-destructive. Another method is to assess soil organic carbon, where researchers have to collect soil samples in their study areas and analyse them in the lab. Researchers have collected soil samples in various ways in terms of depth as there is no standard rule that strictly states that soil samples should only be collected at a certain depth. Ten out of 14 papers analysed show that researchers favour the combination of both destructive and non-destructive methods for carbon assessment, including the soil carbon pool as well.

Overall, carbon pools found in dry areas are in the vegetation (trees and shrubs), herbaceous layer (grass and herbs), litter/debris and soil, which are the same carbon pools found in the ProNamib area. The percentages of these carbon pools vary depending on the location and type of ecosystem. However, globally, the soil is considered to be the largest terrestrial carbon pool (80%), grasslands cover 10% and the vegetation pool covers 15% (Petrokofsky *et al.,* 2012a, Ghosh and Mahanta, 2014). The carbon pool in litter in dry areas is relatively small as there is not enough biodiversity/vegetation to contribute to litter production, therefore dead organic matter and litter together account for the remaining 5%.

Table 2. Existing methods suitable for assessing carbon stock in dry areas. Paper- are the selected articles on carbon assessment. Carbon credit- whether the method was used for carbon accreditation. Y-yes, N-No, NA-data not available.

Citation	Papers	Woody Vegetation	Herbaceous	soil	Litter	Management/Land use	Annual rainfall	Habitat/Carbon pool	Study design	AGB	BGB	Soil depth	Analysis	Carbon credit
(Alamgir and Al-Amin 2008)	P4	Y	Y	N	Y	Forest	NA	NA	Destructive & Non-destructive	Y	Y	NA	Allometric equations & lab analysis	N
(Albaladejo *et al.* 2013)	P5	N	N	Y	N	Semi-arid Mediterranean	330 mm	Forestland, shrubland, and cropland	Non-destructive	N	Y	100cm	Lab analysis	N
(Daryanto *et al.* 2013)	P7	Y	Y	Y	N	Extensive grazing	312mm	NA	Destructive & Non-destructive	Y	Y	30cm	Allometric models & lab analysis	N
(Torres *et al.* 2021)	P8	Y	Y	Y	Y	NA	NA	Dense and Open Caatinga, Pasture fields and Crop fields	Destructive & Non-destructive	Y	Y	100cm	Allometric models & lab analysis	N
(Fierer *et al.* 2003)	P11	N	N	Y	N	Reserve	500mm	NA	Non-destructive	N	Y	25cm	Lab analysis	N
(Wang *et al.* 2014)	P13	Y	Y	Y	N	Desert Grasslands	250 mm to 50 mm	NA	Destructive & Non-destructive	Y	Y	100cm	Walkley-Black, Allometric models	N
(Reeder and Schuman 2002)	P16	N	Y	Y	N	Two semi-arid grasslands	Mixed-grass=366 mm, Short-grass steppe=325mm	mixed-grass prairie & short-grass steppe	Destructive & Non-destructive	Y	Y	90cm	Walkley-Black % Equations -Grass	N
(Nafus *et al.* 2009)	P18	N	Y	N	N	Semidesert Rangeland	207 mm	Grazed and Ungrazed	Destructive & Non-destructive	Y	N	NA	Allometric models	N
(Odorico *et al.* 2014)	P19	Y	N	N	N	Savannah ecosystems - Kalahari Transect	Shakawe= 539 mm, Kuke= 439 mm ,Tshane =358 mm & Bokspits= 177 mm.	NA	Destructive & Non-destructive	Y	Y	NA	Allometric models	N
(Mills and Cowling 2010)	P20	N	N	Y	N	Nature Reserve	349mm	NA	Non-destructive	N	Y	102cm	Walkley–Black method	N
(Teshome *et al.* 2022)	P22	Y	N	N	N	Forest	NA	NA	Destructive & Non-destructive	Y	Y	NA	Allometric models	N
(Stoffberg *et al.* 2010)	P24	Y	N	N	N	(City of Tshwane) Urban street trees	NA	Suburb	Non-destructive	Y	N	NA	Allometric models	N
(Zhang *et al.* 2022)	P25	N	Y	N	N	Grassland	Inner Mongolia=40 to 580 mm, Suli=200–400 mm, SRYR=530 mm	Grassland	Destructive & Non-destructive	Y	N	NA	Canopy height model (CHM) algorithms	N
(Yuan *et al.* 2021)	P28	Y	Y	Y	N	Grassland	343 to 500 mm	FG, UG & CK	Destructive & Non-destructive	Y	Y	100cm	Allometric models and Lab analysis	N
(Verified Carbon Standard 2012)	Verra carbon registry	Y	Y	Y	Y	In all different managemnt areas, e.g Agricultural area, private conservation reserves	NA	All different carbon pools	Destructive & Non-destructive	Y	y	At least 30cm deep	Allometric models and Lab analysis	Y
https://www.cleanenergyregulator.gov.au/ERF	Australian carbon registry	Y	Y	Y	Y	In all different managemnt areas, e.g Agricultural farming, conservation areas	NA	All different carbon pools	Destructive & Non-destructive	Y	Y	At least 30cm deep	Allometric models and Lab analysis	Y

4.2 Map and investigate the spatial pattern of the carbon stock and investigate the key drivers of the carbon stock at PNNR and compare that with the neighbouring livestock farm.

4.2.1 Carbon stock distribution among the area's ecosystems and management units

Figure 15 is showing the total carbon stock distribution over the different carbon pools. The ecosystems of this area holds a total of 18 tonnes ha^{-1} on average, however eighty to night percent of this carbon is stored in the soil. Among the ecosytems, the mountain appears to have the highest total carbon stock, while the lowest is recorded in the river habitat. Figure 16 is showing the total carbon stock distribution over the different carbon pools for management units. The ''livestock'' unit have the highest total carbon stock.

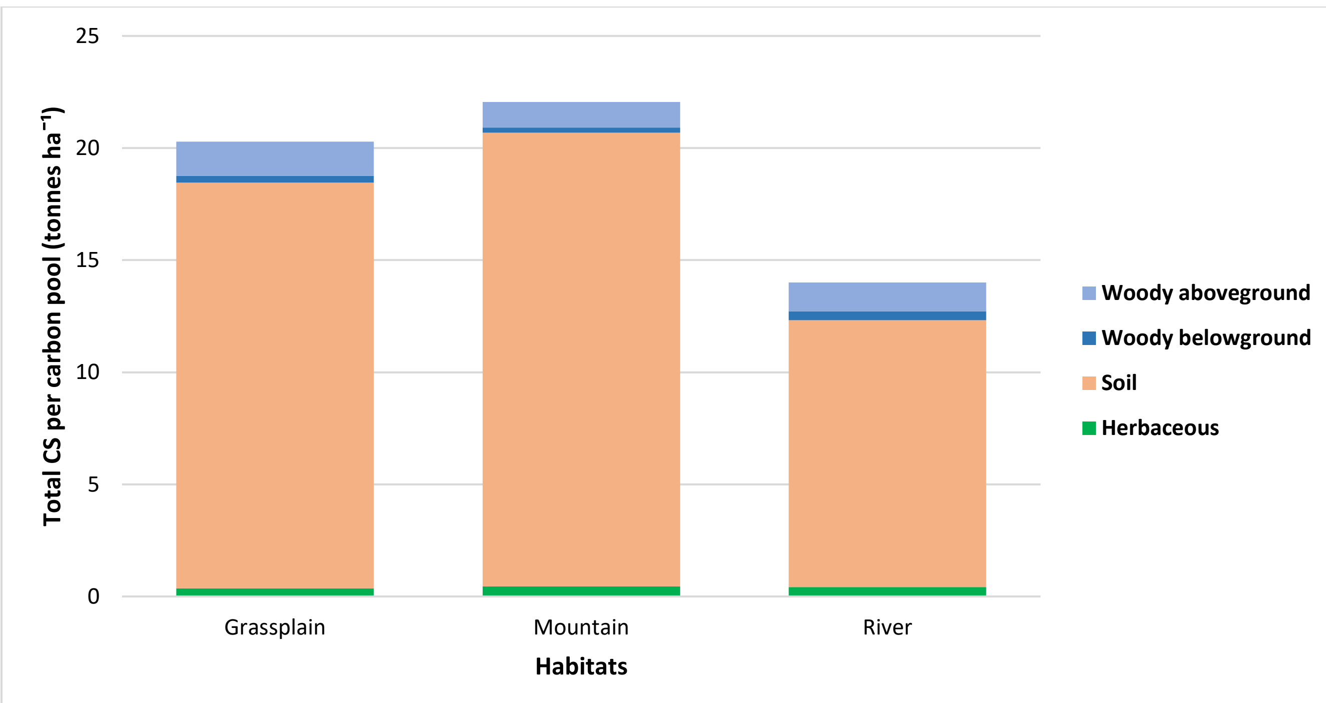

Figure 15 Total carbon stock distribution over the different carbon pools for habitats.

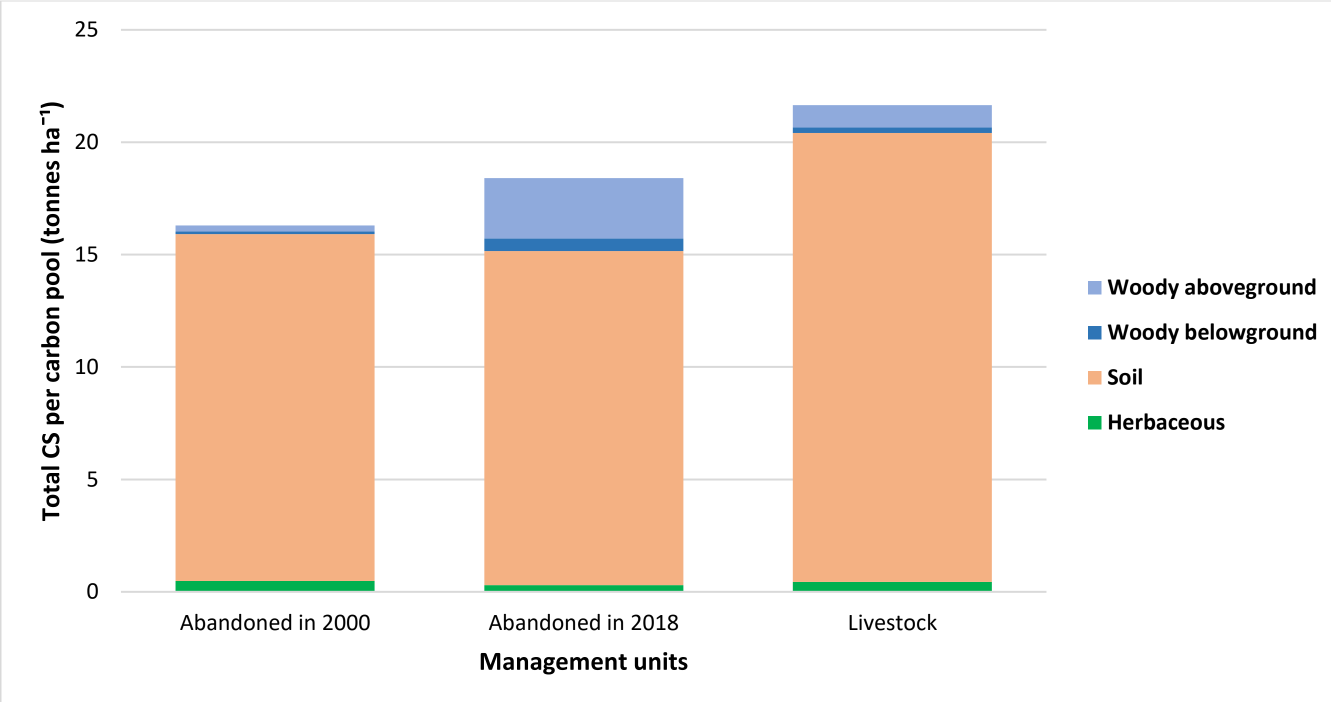

Figure 16 Total carbon stock distribution over the different pools for management units

Figure 17 shows that the ''livestock'' unit have the overall highest total carbon stock in the study area, followed by the ''abandoned in 2018'', while the ''abandoned in 2000'' recorded the lowest total carbon stock.

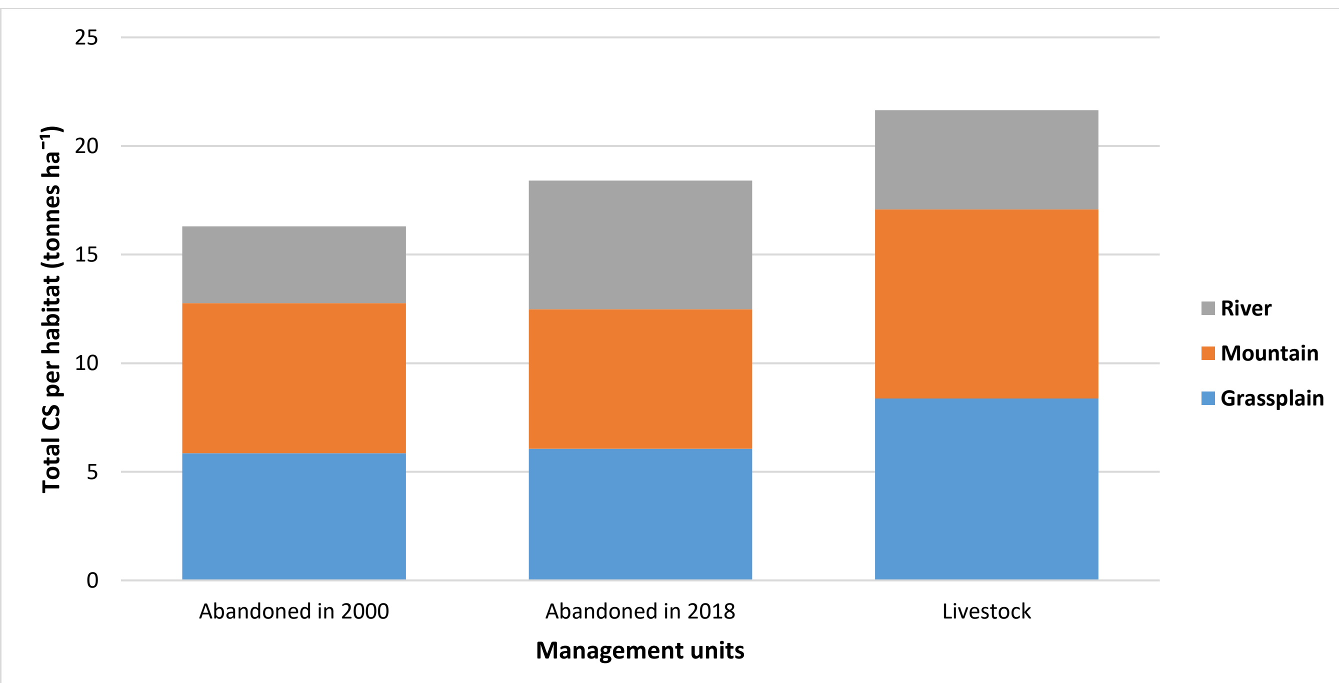

Figure 17 Total carbon stock distribution over the differerent habitats per management unit

4.2.2 Carbon stock distribution per individual carbon pool

Soil organic carbon (soc)

Figure 18 shows the soil organic carbon differences between habitats. The mountain habitat shows the highest SOC in all the three management units, however the linear regression only showed that SOC is significantly lower in the river habitat (p=0.01) (Table 1). Among the management units, the ''livestock'' unit has the highest SOC in the area, followed by the ''abandoned in 2000'' unit and the lowest SOC was found in the ''abandoned in 2018'' (Figure 19). The outlier in the ''abandoned in 2000'' is from one of the mountain plots, and it was the only mountain plot where the soil sample could be collected up till a 30cm depth.

Table 3 Linear regression for soil organic carbon (SOC)

```
lm(formula = SOC..t.ha. ~ Management.units * HABITATS - 1, data = SOIL)

Residuals:
   Min     1Q Median     3Q    Max
-7.790 -2.565 -0.105  2.190 27.170

Coefficients:
                                                Estimate Std. Error t value Pr(>|t|)
Management.unitsAbandoned in 2000                 11.420      1.477   7.732 2.52e-11 ***
Management.unitsAbandoned in 2018                  9.960      1.477   6.744 2.10e-09 ***
Management.unitsLivestock                         14.800      1.477  10.021 7.73e-16 ***
HABITATSMountain                                   2.010      2.089   0.962   0.3388
HABITATSRiver                                     -5.430      2.089  -2.600   0.0111 *
Management.unitsAbandoned in 2018:HABITATSMountain -1.680      2.954  -0.569   0.5711
Management.unitsLivestock:HABITATSMountain        -0.060      2.954  -0.020   0.9838
Management.unitsAbandoned in 2018:HABITATSRiver    4.950      2.954   1.676   0.0976 .
Management.unitsLivestock:HABITATSRiver           -1.020      2.954  -0.345   0.7308
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 4.67 on 81 degrees of freedom
Multiple R-squared:  0.8727,	Adjusted R-squared:  0.8585
F-statistic: 61.68 on 9 and 81 DF,  p-value: < 2.2e-16
```

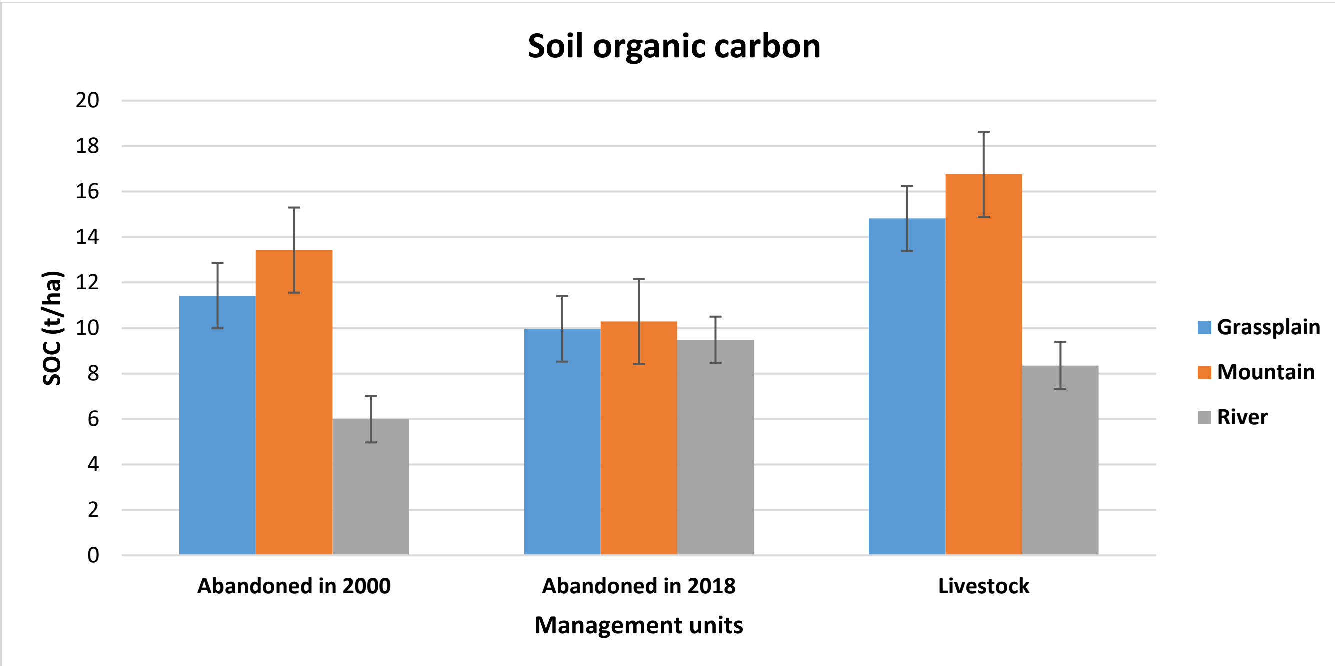

Figure 18 Average soil organic carbon (SOC) stock per habitat.

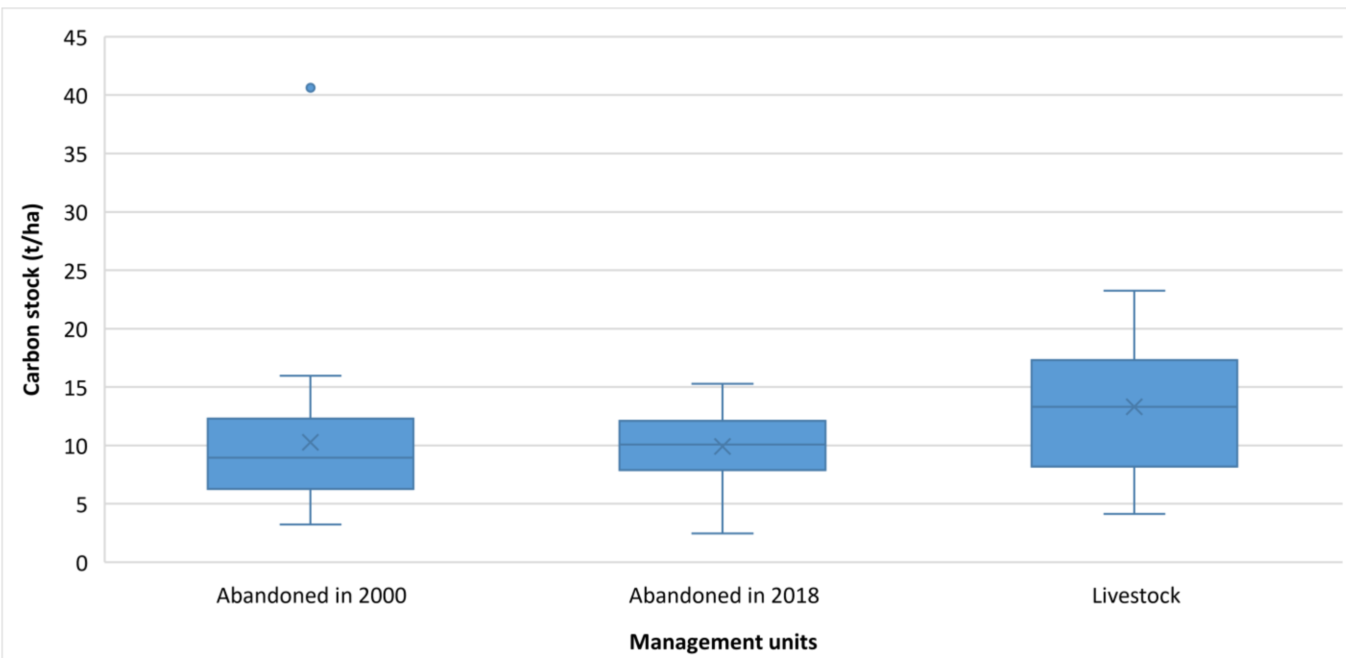

Figure 19 Average soil organic carbon stock (SOC) per management unit.

Aboveground biomass

The above ground biomass of multi-stemmed shrubs such as *Rhigozium trichotomum*, *Catophractes alexandri*, and *Monechma* species, was determined with model4 of Conti et al. (2019). Trees and large shrubs such as *Acacia (Vachellia) erioloba*, *Acacia (Senegalia) mellifera*, *Boscia foetida* and *Moringa ovalifolia* were calculated with Chave's model and compared to model 1 of Conti.

Figure 20 shows that multi-stemmed woody species (small shrubs) stores more carbon in the river habitats in all three management units, followed by mountain habitat and lastly, the grassplain habitat. There is an interaction between management units and habitats. Further, both the mountain and river habitats showed a significant difference in all the management units (mountain *p*-value = 2.63e-08, river *p*-value= 2.46e-10) (Table 4). The results also indicated that the management history had no to a low significant influence within the river habitat, (''abandoned in 2018'' *p*-value= 0.03 ''livestock'' *p*-value= 0.05).

Table 4 Linear regression result for multi-stemmed species (Conti model4)

```
lm(formula = ms ~ Mgtunits * Habitats - 1, data = woodylog)

Residuals:
    Min      1Q  Median      3Q     Max
-12.725  -1.487  -0.186   1.141  13.346

Coefficients:
                                          Estimate Std. Error t value Pr(>|t|)
MgtunitsAbandoned in 2000                  -16.938      1.561 -10.849  < 2e-16 ***
MgtunitsAbandoned in 2018                  -10.106      1.561  -6.473 6.86e-09 ***
MgtunitsLivestock                          -15.600      1.561  -9.992 8.80e-16 ***
HabitatsMountain                            13.608      2.208   6.164 2.63e-08 ***
HabitatsRiver                               15.954      2.208   7.226 2.46e-10 ***
MgtunitsAbandoned in 2018:HabitatsMountain  -4.912      3.122  -1.573   0.1196
MgtunitsLivestock:HabitatsMountain          -0.456      3.122  -0.146   0.8843
MgtunitsAbandoned in 2018:HabitatsRiver     -6.868      3.122  -2.200   0.0307 *
MgtunitsLivestock:HabitatsRiver             -6.050      3.122  -1.938   0.0561 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.937 on 81 degrees of freedom
Multiple R-squared:  0.7765,    Adjusted R-squared:  0.7517
F-statistic: 31.27 on 9 and 81 DF,  p-value: < 2.2e-16
```

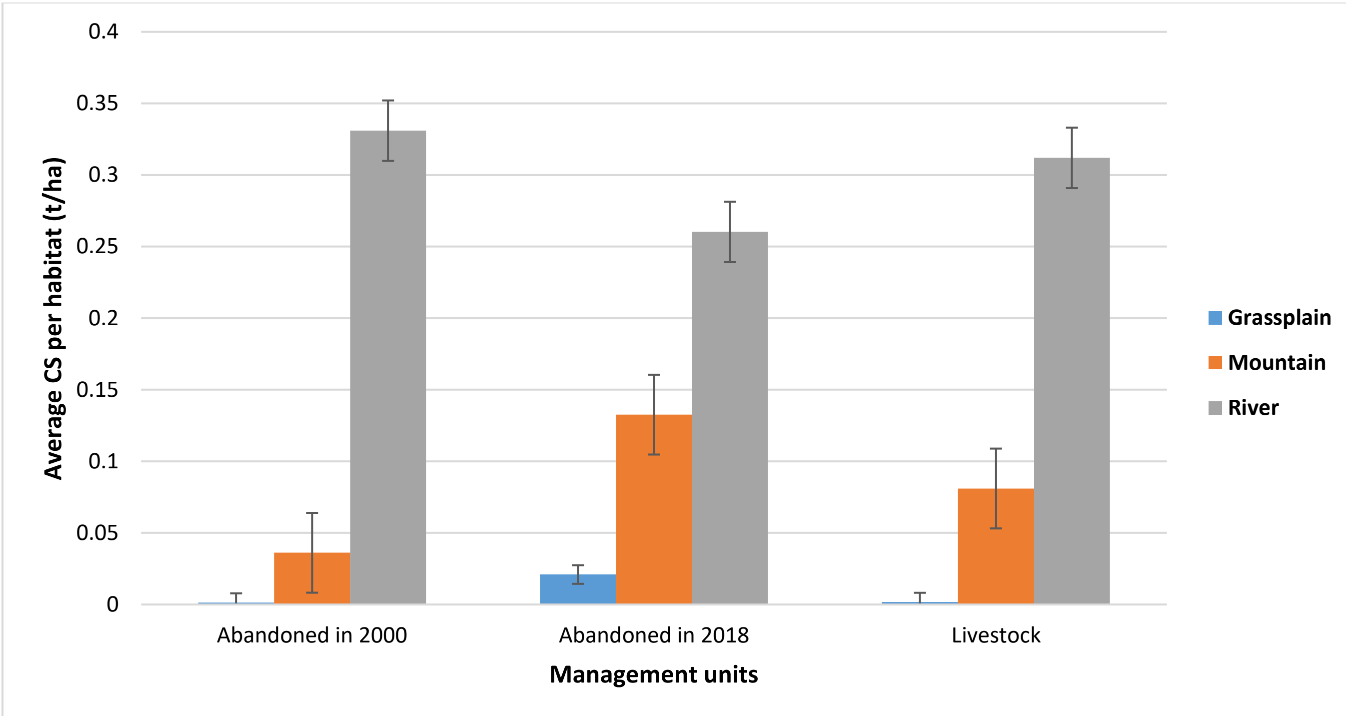

Figure 20 Average aboveground carbon stock per habitat and management unit in multi-stemmed woody species (Model4)

The carbon stock in trees and large shrubs appears to be high in the grassplain habitat in the "livestock" and ''abandoned in 2018'' management units, however in the ''abandoned in 2018'' the measured carbon in the mountain habitat is slightly higher than the grassplain habitat (Figure 21). In the "abandoned in 2000" management unit, there were no trees recorded in both the grass plain or mountain habitat plots. There is an interaction between the management units and habitats (Table 5). The statistical test shows that both the mountain and river habitats are highly significant in all the management units (mountain *p*-value = 7.93e-08, river *p*-value= 1.15e-07). The results also indicated that the management history has a highly significant influence in the river habitat (''abandoned in 2018'' *p*-value= 0.005).

Table 5 Linera regression output for trees and large shrubs (Chave's model)

```
lm(formula = chave ~ Mgtunits * Habitats - 1, data = woodylog)

Residuals:
    Min      1Q  Median      3Q     Max 
-15.445  -2.381   0.000   1.824  18.506 

Coefficients:
                                         Estimate Std. Error t value Pr(>|t|)    
MgtunitsAbandoned in 2000                 -16.579      1.985  -8.350 1.53e-12 ***
MgtunitsAbandoned in 2018                 -10.322      1.985  -5.199 1.47e-06 ***
MgtunitsLivestock                         -15.860      1.985  -7.988 7.93e-12 ***
HabitatsMountain                           16.579      2.808   5.905 7.93e-08 ***
HabitatsRiver                              16.332      2.808   5.817 1.15e-07 ***
MgtunitsAbandoned in 2018:HabitatsMountain  -8.081      3.971  -2.035  0.04512 *  
MgtunitsLivestock:HabitatsMountain          -2.150      3.971  -0.542  0.58960    
MgtunitsAbandoned in 2018:HabitatsRiver    -11.350      3.971  -2.858  0.00541 ** 
MgtunitsLivestock:HabitatsRiver             -7.493      3.971  -1.887  0.06274 .  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 6.278 on 81 degrees of freedom
Multiple R-squared:  0.6916,	Adjusted R-squared:  0.6574 
F-statistic: 20.19 on 9 and 81 DF,  p-value: < 2.2e-16
```

Chave’s model shows the same trends as Conti’s model1, where the carbon stock is higher in the grass plain habitats in the “livestock” unit. However, there is a huge difference in the ‘’abandoned in 2018’’ unit (Figure 21). The carbon stock in grassplain and river have doubled, while the mountain carbon stock declined from 1.7 t/ha to 1.0 t/ha. There was an interaction effect between management units and habitats (Table 6). Mountain and river habitats showed a highly significant difference (mountain *p*-value = 7.93e-08, river *p*-value= 1.15e-07).

Table 6 Linear regression output for trees and large shrubs (Conti model1)

```
lm(formula = conti ~ Mgtunits * Habitats - 1, data = woodylog)

Residuals:
    Min      1Q  Median      3Q     Max
-19.471  -1.842   0.000   2.115  18.587

Coefficients:
                                         Estimate Std. Error t value Pr(>|t|)
MgtunitsAbandoned in 2000                 -16.579      2.047  -8.097 4.84e-12 ***
MgtunitsAbandoned in 2018                 -10.274      2.047  -5.018 3.04e-06 ***
MgtunitsLivestock                         -15.851      2.047  -7.741 2.42e-11 ***
HabitatsMountain                           16.579      2.896   5.725 1.69e-07 ***
HabitatsRiver                              16.802      2.896   5.803 1.22e-07 ***
MgtunitsAbandoned in 2018:HabitatsMountain  -8.203      4.095  -2.003   0.0485 *
MgtunitsLivestock:HabitatsMountain         -2.403      4.095  -0.587   0.5589
MgtunitsAbandoned in 2018:HabitatsRiver   -10.145      4.095  -2.477   0.0153 *
MgtunitsLivestock:HabitatsRiver            -7.857      4.095  -1.919   0.0585 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 6.475 on 81 degrees of freedom
Multiple R-squared:  0.673,     Adjusted R-squared:  0.6367
F-statistic: 18.52 on 9 and 81 DF,  p-value: 2.497e-16
```

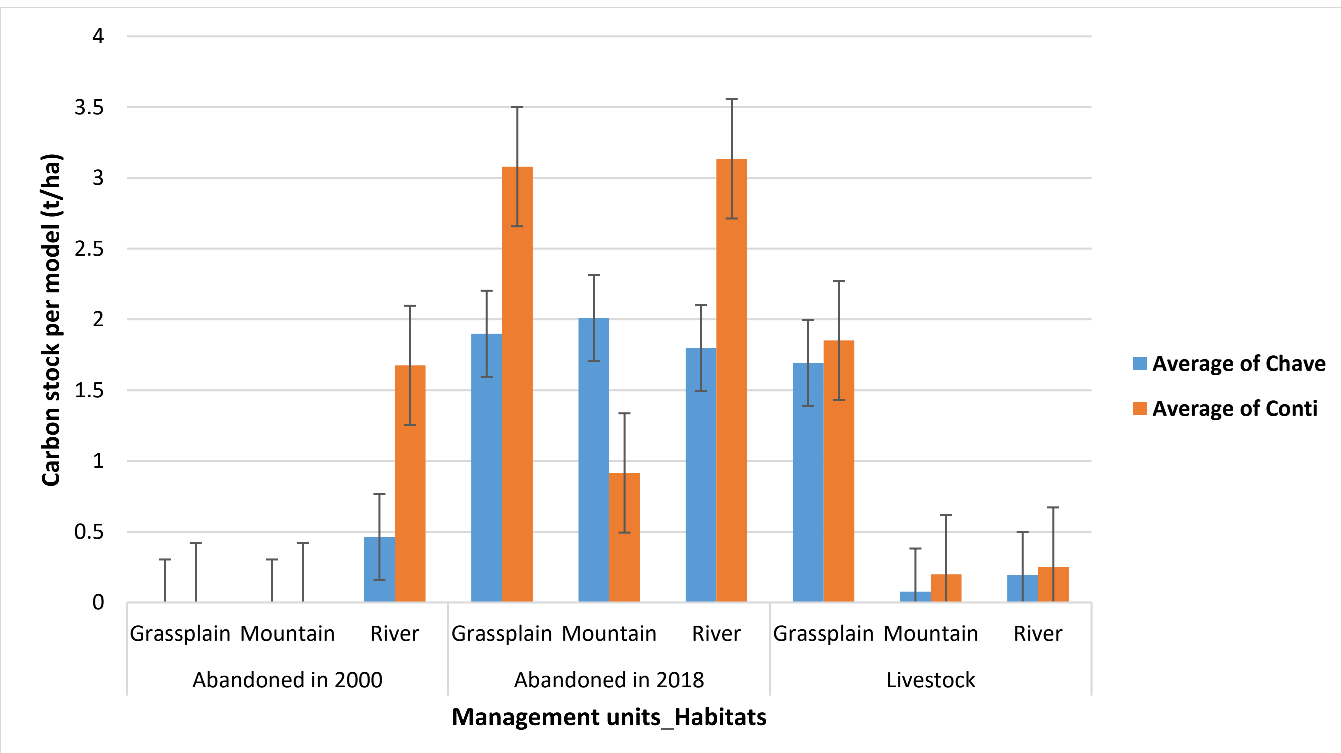

Figure 21 Comparison between Chave's model and Conti's model (trees and large shrubs)

Figure 22 shows the distribution of carbon stock in woody species (trees & large shrubs and multi-stemmed shrubs) over habitats. The river habitat has the largest carbon stock stored in woody species, followed by the grassplain, while the mountain appears to have the least carbon stock stored. Among management units, the “abandoned in 2018’’ has the highest woody carbon stock storage, while the lowest is recorded in the ‘’abandoned in 2000’’ (Figure 23).

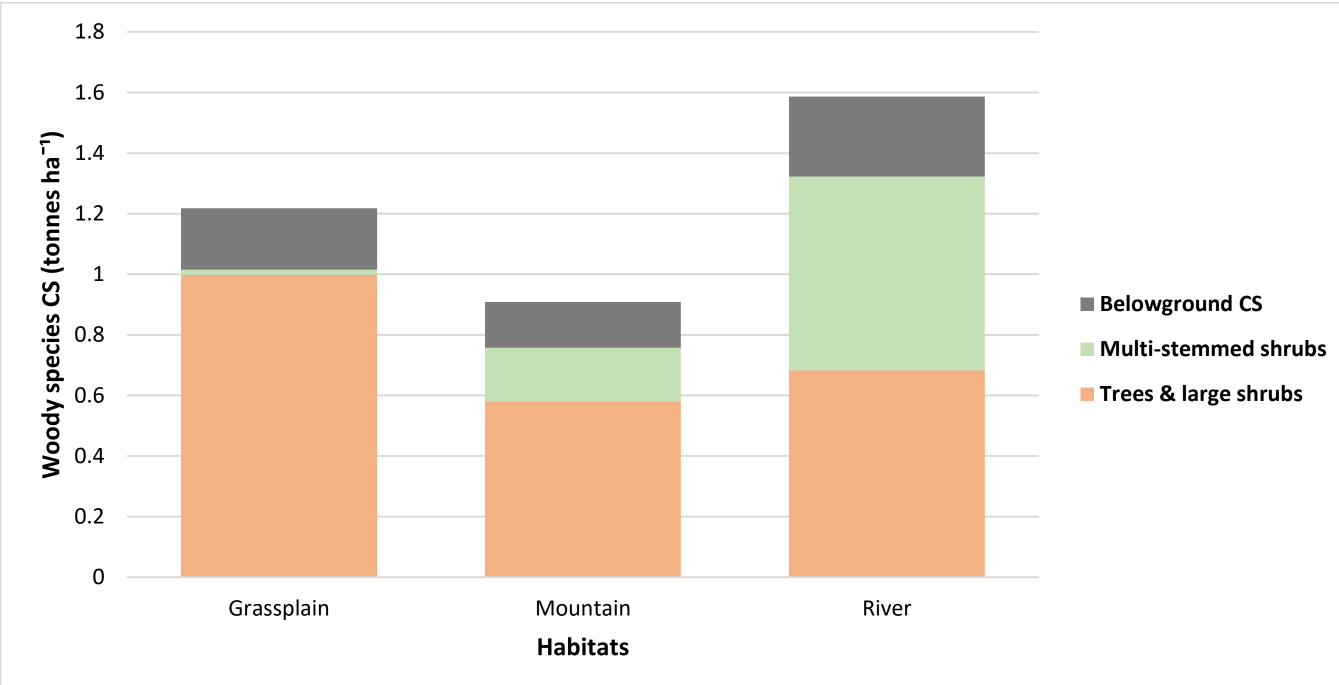

Figure 22 Woody species’ carbon stock distribution over habitats

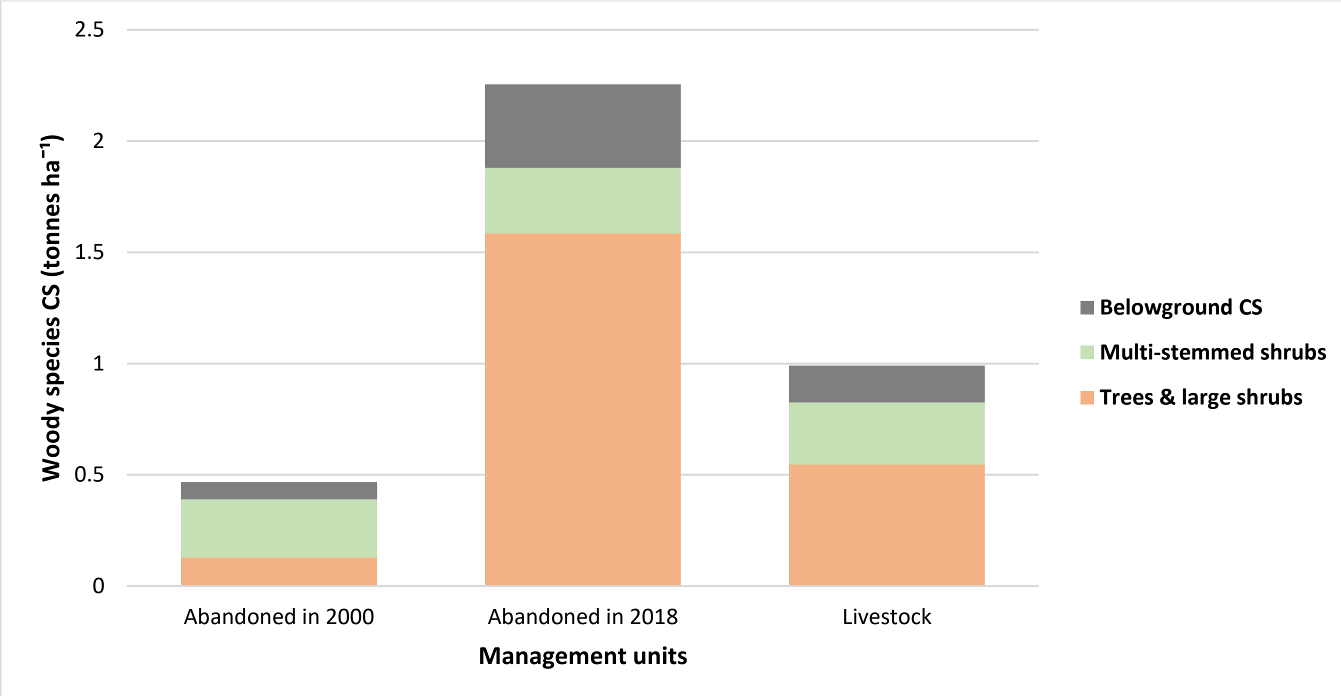

Figure 23 Total woody species carbon stock per management unit.

Figure 24 shows the herbaceous carbon stock per habitats in the three management units. There is no significant difference among the habitats (Table 7).

Table 7 Linear regression output for herbaceous plants

```
lm(formula = cs ~ mgt * habitat - 1, data = HERBS)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.38306 -0.09579 -0.03264  0.07808  0.67835 

Coefficients:
                                    Estimate Std. Error t value Pr(>|t|)    
mgtAbandoned in 2000                 0.27061    0.05171   5.234 1.28e-06 ***
mgtAbandoned in 2018                 0.20729    0.05171   4.009 0.000135 ***
mgtLivestock                         0.23150    0.05171   4.477 2.45e-05 ***
habitatMountain                      0.04682    0.07313   0.640 0.523769    
habitatRiver                         0.11245    0.07313   1.538 0.128009    
mgtAbandoned in 2018:habitatMountain -0.03114    0.10341  -0.301 0.764114    
mgtLivestock:habitatMountain         0.08634    0.10341   0.835 0.406239    
mgtAbandoned in 2018:habitatRiver   -0.16039    0.10341  -1.551 0.124820    
mgtLivestock:habitatRiver           -0.05907    0.10341  -0.571 0.569466    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1635 on 81 degrees of freedom
Multiple R-squared:  0.7654,	Adjusted R-squared:  0.7393 
F-statistic: 29.36 on 9 and 81 DF,  p-value: < 2.2e-16
```

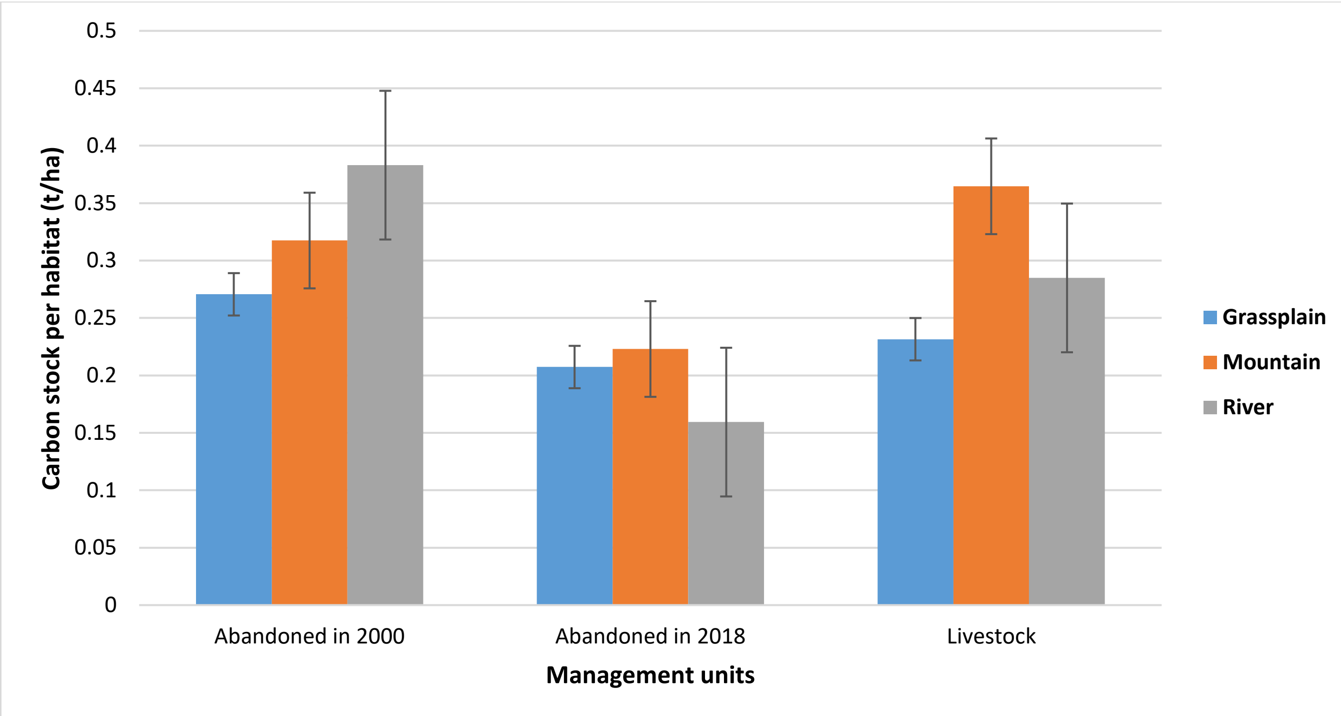

Figure 24 Average herbaceous carbon stock per habitat.

Figure 25 shows that the ''abandoned in 2000'' unit has the highest herbaceous carbon stock recorded, while the ''abandoned in 2018'' has the lowest biomass carbon stock.

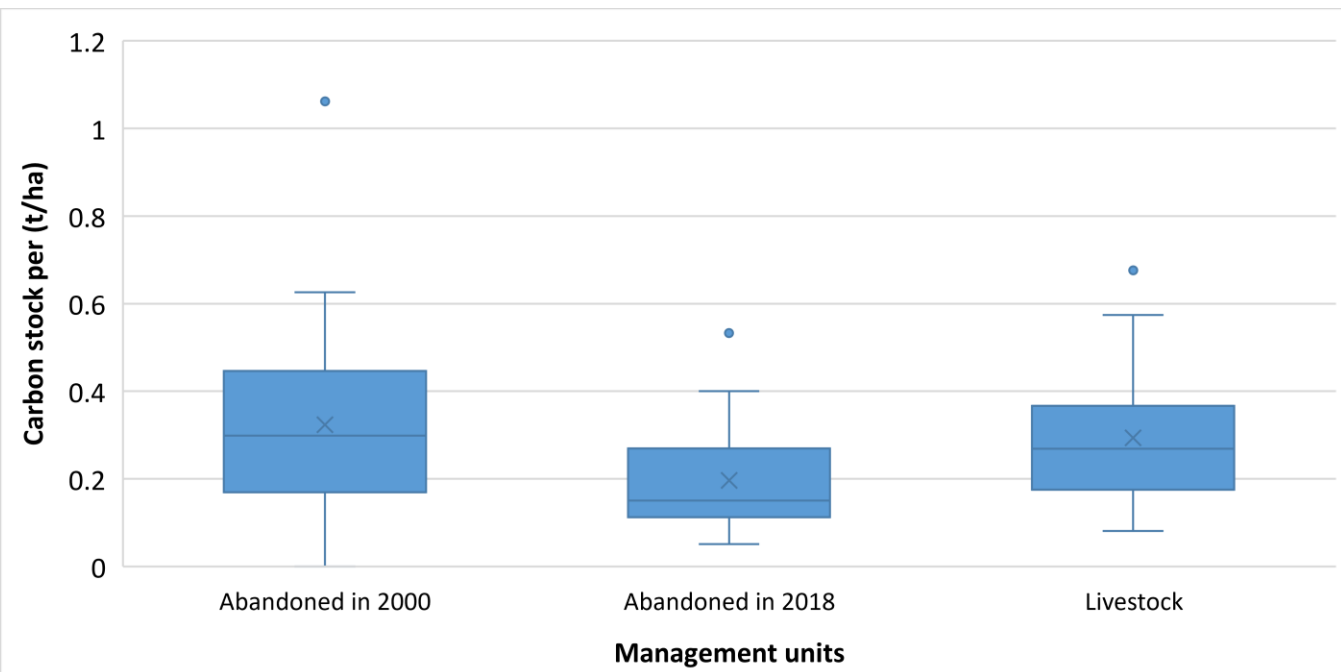

Figure 25 Average herbaceous carbon stock per management unit.

Vegetation aboveground and belowground carbon

Figure 26 shows the whole area’s total aboveground and belowground carbon stock of the carbon pools in the vegetation combined (woody and herbaceous plants). The greatest vegetation carbon stock is recorded in the ‘’abandoned in 2018’’ unit, whereas the least vegetation carbon stock is recorded in the ‘’abandoned in 2000’’.

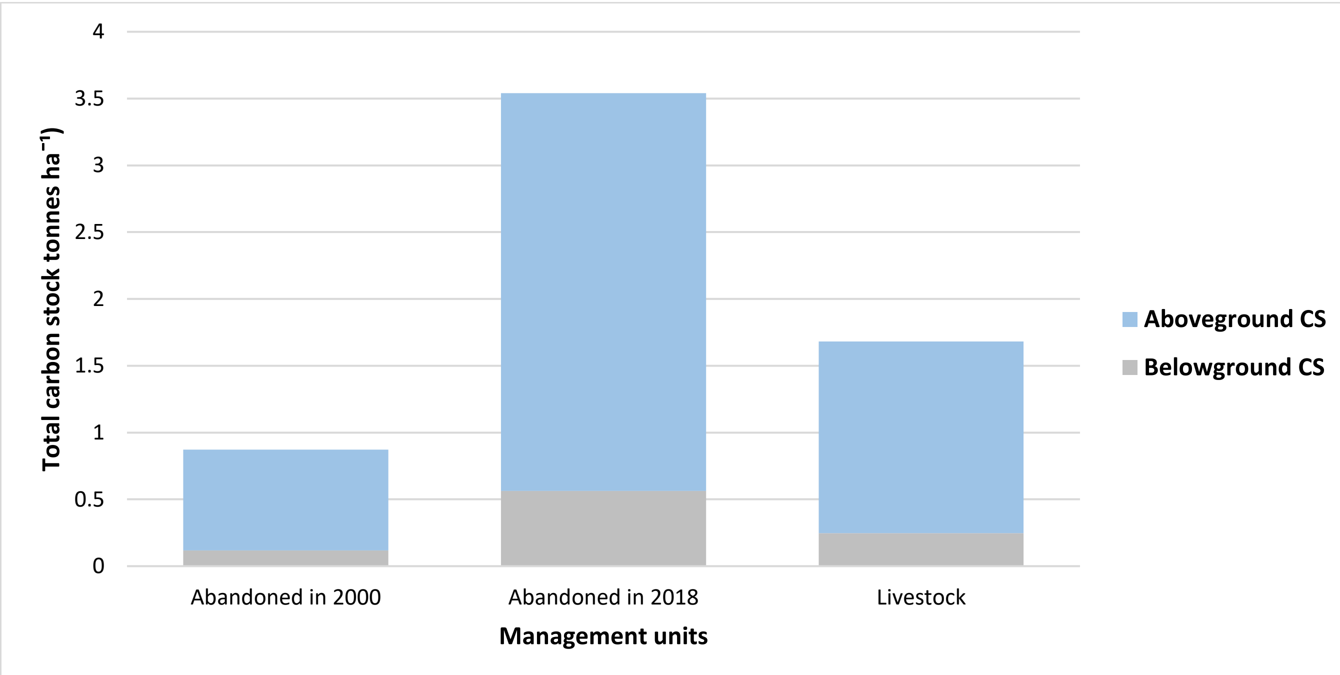

Figure 26 The vegetation (woody and herbaceous) total aboveground and belowground carbon stock per management unit.

Chapter 5: Discussion

5.1 Defining appropriate methods for determining the carbon stock in arid environments.

In dry conservation areas such as the ProNamib, a destructive method for trees and shrubs is not suitable due to its few scattered plant species and its current land use objective which is to transform former degraded livestock farms into a conservation reserve in order to restore the biodiversity in the area. Even though the non-destructive method is not the most accurate when it assessing carbon, the use of existing general allometric models would be the best for conserving the areas' biodiversity.

Previous carbon studies that used the destructive method have made it easier for future carbon studies as they have documented wood-specific densities and developed allometric equations for many species globally. This allows future carbon researchers to focus mainly on the non-destructive method in areas where the destructive method is not applicable or suitable. However, arid areas' wood density data such as the ProNamib, is limited and difficult to attain. Nevertheless, studies like Conti *et al.* (2019) and Chave *et al.* (2014) developed generic allometric models that don't require any harvesting data and they are suitable for dry areas as well. These are the allometric equations this study used to estimate carbon stock in vegetation (trees and shrubs) species.

Herbaceous biomass analysis is mostly assessed through oven drying or air drying to get the dry weight. For soil analysis, some researchers used Walkley-black (WB), while others used the dry-combustion/Loss-on ignition method (LOI). Wang *et al.* (2013) found that the LOI was more reliable and could produce accurate estimates of SOC for arid soils compared to the WB method. However, Ali (2021) established that both the LOI and the WB methods were reliable. He further stated that the LOI method is suitable for soils with a large amount of soil organic matter and low clay content, while WB method is best suited for soils with high clay content and calcareous soils.

All carbon registries such as Verra/VCS registry (VM0021 and VM0022 protocols) and ACCU have their own data collection and analysis standards that need to be followed when carbon studies are aiming to apply for carbon credits.

5.2 Map and investigate the spatial pattern of the carbon stock and investigate the key drivers of the carbon stock at PNNR and compare that with the neighbouring livestock farm.

5.2.1 Carbon stock distribution among the area's ecosystems and management units

The largest carbon pool in the ProNamib area is stored in the soil (50.24 tonnes ha^{-1}). This resembles Gebregergs *et al.* (2019) study in a semi-arid environment of northern Ethiopia, where they found higher carbon stock in the soil than in biomass across all the three management areas (open grazing , five year grazing exclosure and ten year grazing exclosure). Dabasso *et al.* (2014) also stated that they found the highest carbon storage in the soil (98.39%) compared to woody and herbaceous vegetation in the study they did in Kenya.

The second largest carbon pool is the woody vegetation (4.87 tonnes ha^{-1}). Even though the woody plants are scattered and mostly in the rivers, the large old *Acacia* species stores a significant amount of carbon. All vegetation types (trees, shrubs, grasses and herbs) play an important role in sequestering carbon in all different areas including drylands, however, trees are more effective due to their big sizes and longer lifespan. Therefore, the amount and type of vegetation cover in dry areas can have a substantial influence on the amount of carbon that can be stored in the soil and biomass (Atsbha *et al*., 2019). The herbaceous carbon pool has the lowest carbon stock storage in the area (1.22 tonnes ha^{-1}).

The greatest carbon stock is stored in the mountain habitat (22.05 tonnes ha^{-1}), compared to the grassplain and river habitats. High soil organic carbon is what contributed to the overall mountain total carbon stock, because mountain habitat has the highest soil organic carbon across all the three management units.

In terms of management units, the ''livestock'' unit has the highest carbon stock in the area (21.64 tonnes ha^{-1}), the second highest is recorded in the ''abandoned in 2018'' unit (18.40 tonnes ha^{-1}). These two management units are more towards the East, which is the higher rainfall section in the study area. The lowest carbon stock was found in the ''abandoned in 2000'' unit (16.29 tonnes ha^{-1}), this management unit is more towards the low rainfall section, in the South and West side of the area, this could be the reason for low carbon stock.

The differences in the carbon distribution in this area does not mean that it is caused by the current land management, they could have existed before the change in land management. It is alos important to note that the prior land managements among the management units before abandonedment are not known.

5.2.2 Carbon stock distribution per individual carbon pool

Soil organic carbon

As reported in past global studies that focused on quantifying soil carbon, especially in grasslands, soil organic carbon stocks differ greatly among climatic regions and soil types (Dondini *et al.,* 2023). This study found that the SOC is the highest in mountain habitat in all three management units, however, in the ''abandoned in 2018'' unit, the total carbon stock is almost the same between all the habitats (Figure 18). 28 mountain soil samples were collected at a depth of 20cm and above, one was at 23cm, and only one of them went to a 30cm depth. All the soil samples collected in river and grassplain habitats went to a 30cm depth except for three river samples.

Previous studies found that SOC decline with depth (Grandy and Robertson, 2007; Anokye *et al.,* 2021, Ntukey *et al.,* 2022). They found that the upper soil (0cm-20cm) stores the highest SOC, this corresponds with this study's results for the reason that, even though this study's soil samples were not analysed per depth, the SOC of all the 28 soil samples collected at a 20cm depth and above is higher than the SOC collected at a 30cm depth. But then again, the sole 30cm mountain plot recorded the highest SOC of all the soil samples collected, which somehow contradicts the depth notion. This begs the question whether the mountain habitat stores more SOC in the area compared to grassplain and river or is it just in that specific plot.

The mountain SOC being the highest could also be due to less or no disturbances since both humans and animals barely utilise this habitat compared to grassland and rivers (Malepfane *et al.,* 2022). This habitat has the highest species diversity in the area and studies have shown that increased biodiversity can lead to higher levels of SOC (Wiesmeier *et al.,* 2019). This is because a more diverse range of plant species can lead to a greater variety of root systems, which in turn can increase the amount of organic matter that is added to the soil. Moreover, a greater variety of microorganisms in the soil can also contribute to increased SOC, as these organisms break down organic matter and release carbon into the soil. As for low SOC in the river habitat, it might be due to water runoff during the rainy season because not all the waterinfiltrates the soil. Water runoff is said to easily transport SOC, as well the wind as most of the SOC is stored in the upper soil (Lal, 2003).

Literature states that bulk density has an impact on aeration, water infiltration as well as plant growth (Throop *et al.,* 2012), therefore it plays a vital part in determining SOC. In this study, it was not sampled with the right equipment in the field, as soil samples were collected with a small spade. This inaccurate assessment could have overestimated or underestimated the SOC results, especially in the mountains where samples were smaller.

The soil types varied in different plots, some were sandy, loamy-sand and some had clay. Previous studies observed that soil type can have a significant impact on SOC in dry areas. In general, soils with higher clay content tend to have higher SOC levels compared to sandy soils. This is due to greater water-holding capacity that clay soils possess, which allows for the retention of organic matter and reduces the degree of decomposition. However, in arid and semi-arid regions, soil type may not be the only factor influencing SOC levels, other factors such as precipitation, vegetation cover, land use and temperature can also play important roles (Wiesmeier *et al.,* 2019). For example, in areas with low precipitation such as the ProNamib area, even clay soils may have low SOC levels due to limited plant growth and minimal organic matter inputs.

The area's vegetation is scattered and does not necessarily provide a favourable plant cover especially in the grassplain habitat and most of the plants are seasonal depending on the amount of rain received. The cover and type of vegetation are said to have an effect on the circulation of SOC in an ecosystem/area (Zhu *et al.,* 2017). With this type of vegetation cover and type, it will be a challenge for the area to accumulate soil carbon as there will not be much litter to decompose which in turn leads to improved soil organic carbon (Lal, 2003). By employing suitable farming practices that involve minimal disturbance of the soil and encourage carbon sequestration, the loss of carbon may be able to slow down or even reverse.

SOC is the highest in the mountain habitat (20.23 tonnes), the grassplain SOC is slightly lower (18.09 tonnes ha^{-1}), and lastly the river (11.90 tonnes ha^{-1}). In terms of management units. the ''livestock'' unit shows a significant difference from the other two management units, it has recorded the highest SOC (19.96 tonnes ha^{-1}), followed by the ''abandoned in 2000'' with 15.42 tonnes ha^{-1}, while the ''abandoned in 2018'' unit has the lowest SOC (14.86 tonnes ha^{-1}). High SOC in ''livestock'' unit could be due to land use practice, as the place is still having livestock. The cattle hooves might have helped mix manure dump into the soil which increases soil organic matter (Jordon, 2021).

Dondini *et al.* (2023) found that the greatest SOC stock is in temperate regions with low decomposition rates and high productivity of grass, while the lowest SOC stock was recorded in semi-arid and arid regions where biomass production is low hence low carbon inputs into the soil. It is also believed that burrowing animals help maintain and improve soil structure, help mix the organic matter through the soil and their burrows help with water infiltration but unfortunately, this area is not home to many burrowing animals.

Woody species (trees and shrubs)

In all three management units, multi-stemmed shrubs' carbon stock is the highest in river habitats compared to mountain and grassplain habitats. From personal observation in the area, this was evident from the beginning of the study, as the woody species are mostly found in rivers/along the riverbeds. Based on the area's vegetation distribution, the river and mountain habitats are dominated by clustered *Rhigozium trichotomum* bushes as well as a few *Catophractes alexandri* bushes, while the grassplain habitat has scattered trees and large shrubs such as *Acacia* and *Boscia* species.

The trees and large shrubs were analysed with the Chave *et al*. (2014) model and compared to the performance of Conti *et al*. (2019) model1 (as shown in Figure 21), but overall Chave's model is the primary model. This model is said to be the best model and suitable for carbon assessment in Africa when the DBH can be accurately obtained in the field (Abere *et al.,* 2017). The two models showed relatively similar aboveground and belowground carbon stock distribution trends. Conti's model estimates in the river and grassplain appears to have doubled that of Chave's estimates, except in mountain habitat in the ''abandoned in 2018'' unit. Conti's model could have been influenced by the fact that it does not include the variables, such as wood density and the diameter at breast height (DBH) which affects aboveground biomass.

In the ''livestock'' unit, the grassplain has the highest carbon stock compared to river and mountain habitats. This habitat only recorded three woody species and only one of them is a tree (*Acacia erioloba)*. Most *Acacia erioloba* trees found in the area are old and large, which could have influenced the biomass carbon stock results between the three habitats in this unit. Houssoukpèvi *et al*. (2022) and Atsbha *et al.* (2019) stated that the presence of large woody species equates to a large carbon storage.

In the ''abandoned in 2018'' unit, the aboveground carbon stock in trees and large shrubs did not show any significant difference between the habitats, however, carbon in the mountain habitat is slightly higher. This habitat recorded the highest species richness compared to the river and grassplain habitats. Among the plant species found on the mountain were different *Commiphora* species, *Boscia* species, *Acacia mellifera* and *Moringa ovalifolia*. Previous studies found that species richness has a positive effect on the aboveground biomass carbon stock in temperate and tropical areas (Mensah *et al.,* 2016; Ntukey *et al.,* 2022), this could be why the mountain habitat is slightly higher.

The belowground carbon stock shows a similar trend to aboveground carbon in both the multi-stemmed shrubs and trees and large shrubs, because the belowground carbon stock is obtained from the 20% (0.2) of the aboveground value.

The woody carbon stock per habitat is the highest in the river (1.69 tonnes ha^{-1}), followed by the grassplain (1.82 tonnes ha^{-1}), and lastly the mountain (1.36 tonnes ha^{-1}). Topography aspects such as altitude and slope are believed to affect tree species distribution and influence carbon stock (Siraj, 2019). Their study found a decrease in carbon stock with the increase of elevation.

In the management units, the carbon stored in the vegetation of the ʼʼabandoned in 2018ʼʼ unit (3.24 tonnes ha^{-1}) is significantly greater than the carbon stock in the ʼʼlivestockʼʼ (1.24 tonnes ha^{-1}) and ʼʼabandoned in 2000ʼʼ units (0.39 tonnes ha^{-1}). The type and size of woody species found in each of these management units might have influenced the carbon stock total, as it is not certain if the results are based on the management history/land use. The ʼʼabandoned in 2018ʼʼ and ʼʼlivestockʼʼ units are more towards the east side of the area, which is the high rainfall section of the area while the ʼʼabandoned in 2000ʼʼ unit is more towards the west and south sections of the area. This might have also affected the the area's woody carbon distribution. The sampling plots are representative of the study area as they covered all the ecosystem criteria and all the three carbon pools of the study area.

Herbaceous (grass and herbs)

There are a number of factors that could influence the distribution and biomass of herbaceous species in an area, especially in semi-arid area like the ProNamib. The herbaceous cover in 2022 was higher than normal as it was a good rainfall year.

This study found that the mountain habitat recorded the highest carbon stock in two management units, the ʼʼlivestockʼʼ and ʼʼabandoned in 2018ʼʼ. The topography could be the reason for higher herbaceous carbon stock on mountain habitat as animals especially livestock, barely reach and graze on mountains. The herbaceous vegetation is undisturbed in this habitat. Some quadrats comprised of woody species that were below the 50cm height as they were clipped, dried and weighed together with the herbaceous samples. The resurrection bush (*Myrothamnus flabellifolius)* which is among the species dominating mountain habitat was sampled in many quadrats as they are mostly below the 50cm height. These woody species’ weight made a difference to the results because they are heavier than the actual herbs and grasses.

The ‘’abandoned in 2000’’ unit’s carbon stock shows a different distribution over the three habitats, as river habitat has the highest carbon storage. The type of grass species sampled in each plot could have influenced the results, as some plots had a cluster of wet *Stipagrostis* species especially in the river habitat of the ‘’abandoned in 2000’’ unit, while in the other units, some plots only had half dry *Gisekia afrikana*.

In addition to the grazing effect, depending on the study area/ecosystems, the livestock grazing impact can be complex (Dabasso *et al.,* 2014). As the carbon stock can either decline, increase or not even change depending on the ecological factors of the ecosystem in question. Therefore, repeated long-term and more elaborate studies should be performed to better understand biomass carbon stock patterns in dry areas.

Chapter 6: Conclusion and Recommendations

6.1 Conclusion

Among the five carbon pools found in drylands, this study only found three in the ProNamib area (aboveground, belowground and soil). The area does not have sufficient vegetation to produce litter and deadwood carbon pools. It also found that both destructive and non-destructive methods for vegetation assessment are suitable for assessing dry areas' carbon stock. However, the destructive method, in terms of woody vegetation, is labour intensive and costly. Furthermore, it is not ideal in protected areas with limited or sparsely distributed vegetation such as the ProNamib, as the harvesting overthrows the whole objective of conservation and carbon sequestration.

This study found that 80% to 90% of the carbon in the area is stored in the soil, followed by the woody vegetation, while the herbaceous vegetation did not contribute much. Per area's ecosystems the highest carbon stock in the area is recorded in the mountain habitat (22.05 tonnes ha^{-1}), the second highest is recorded in the grassplain habitat (20.28 tonnes ha^{-1}), and the lowest in the in the river habitat (14 tonnes ha^{-1}).

Per management units, the overall carbon stock is the highest in the ''livestock'' unit (21.64 tonnes ha^{-1}), followed by the ''abandoned in 2018'' unit (18.4 tonnes ha^{-1}) and lastly the ''abandoned in 2000'' (16.29 tonnes ha^{-1}).

Per individual carbon pool, the soil organic carbon is highest in the mountain habitat across all the three management units (20.2 tonnes ha^{-1}) , while the lowest is recorded in the river habitats (11.9 tonnes ha^{-1}). Woody species carbon stock is the highest in the ''abandoned in 2018'' unit (aboveground = 2.68 tonnes ha^{-1}, belowground = 0.56 tonnes ha^{-1}), while for habitats, carbon stock is the greatest in grassplain (aboveground = 1.52 tonnes ha^{-1}, belowground = 0.30 tonnes ha^{-1}).

The herbaceous carbon stock does not contribute a noticeable amount of carbon, however, it is higher in mountain habitats (0.45 tonnes ha^{-1}) comopared to the other two habitas.

6.2 Recommendations

- Since the destructive method is not suitable for the ProNamib area, appropriate existing generic allometric equations that fit tropical regions(such as the ProNamib) should be used to estimate woody species carbon stock.
- Soil organic carbon assessment per depth is recommended as this study mixed all soil samples from three different depths into a single sample per plot. The mountain soil samples did not go as deep as 30 cm like the grassplain and river plots, SOC assessment per depth will provide additional data on the area's SOC distribution in different ecoystems. Soil bulk density also needs to be measured in the field with the right equipment for accurate SOC.
- The carbon stock results per carbon pools indicated that the soil stores the largest carbon in the area. Land management should focus on the soil restoration, as well as the woody vegetation as it also stores a significant amount of carbon.
- Monitoring of all carbon pools over time in the exact same plots where this study's data was collected to compare the results is advised. This will help track the effectiveness of the current management practices, provide an in depth understanding of the area's carbon stock distribution which will then guide additional improvements.
- Collaboration and information sharing with farmers, researchers and carbon credit experts could lead to land use management solutions in the ProNamib area.

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Appendices

Appendix 1 Field Sheet for Data Collection

Data Sheet

Plot: ______ **Date:** ______ **Time:** ______ **Observers:** ______

GPS Lat: ______ **GPS Long:** ______ **Accuracy:** ______ **Way Avg:** ______ **Elev:** ______

Strata: ______ **Habitat:** ______ **Plot Position:** ______ **Slope (°):** ______ **Aspect (<):** ______

Soil Type: ______ **Soil 1:** ______ **Soil 2:** ______

Damage: ______ **Cause** ______

Trees & Shrubs

Species	# Stems	Circ base (cm)	DBH (1.3m) cm	Tree hgt (m)	Stem hgt (cm)	Dist pl cen (m)	Can wid 1 (cm)	Can wid 2 (cm)	Phenology	Degree (°)

Grass & Herbs

Quadrat 1		Quadrat 2		Quadrat 3		Quadrat 4		Quadrat 5	
# Species		# Species		# Species		# Species		# Species	
Fresh wgt (g)		F ag wgt (g)		F ag wgt (g)		F ag wgt (g)		F ag wgt (g)	
Dry wgt (g)		D bg wgt (g)		D bg wgt (g)		D bg wgt (g)		D bg wgt (g)	
Spp	Cover	Spp	Cover (%)	Spp	Cover (%)	Spp	Cover (%)	Spp	Cover (%)

Additional Notes:

Appendix 2 The NCRST permit for data collection

NCRST

AUTHORIZATION OF RESEARCH PROJECTS

Authorization is hereby granted in terms of Section 21 of the RST Act No. 23 of 2004, to:

Name: Elizabeth Twitileni Pius

Address: Private Bag 13388, Windhoek,
Namibia

Coworkers: Mandy Scheibe and Dr. Daniel Wyss

Certificate Number (if applicable): RCIV00032018 **Authorization No:** 202209013

Type of Research:
Non- Commercial research and the use of resources be limited to what is in the proposal.

Title of Research Authorized:
Assessment of the carbon pool in the ProNamib Nature Reserve.

Locality:
ProNamib Nature Reserve and the Neighbouring livestock farm (Eckberg)

Duration: 26 September 2022 - 30 September 2023

Research / Sample Collection Conditions:
Refer to research conditions on the next page.

Yours sincerely,

National Commission on Research Science & Technology
26 SEP 2022
P/Bag 13253
Windhoek, Namibia

Ms. Albertina Ngurare
Acting Chief Executive Officer

Head Office: [illegible]

Innovation Hub: [illegible]

Appendix 3 The Soil organic carbon/content raw results (comparison between the Walkley black method and Loss-on ignition method)

Management units	Habitats	Plots	Organic carbon (Loss-on ignition)	Organic carbon (Walkley Black)
Livestock	Mountain	P36	0.831	0.504
Livestock	Mountain	P28	0.787	0.397
Livestock	Mountain	P7	0.750	0.437
Livestock	Mountain	P89	0.751	0.457
Abandoned in 2000	Mountain	P43	0.790	0.431
Abandoned in 2000	Mountain	P9	0.740	0.453
Abandoned in 2000	Mountain	P17	0.728	0.387
Abandoned in 2000	Mountain	P6	1.042	0.365
Abandoned in 2000	Mountain	P23	0.784	0.454
Abandoned in 2018	Mountain	P87	1.091	0.614

Appendix 4 Soil analysis protocols used to analyse the soil samples at the Ministry of Environment, Forestry and Tourism's soil lab.

REPUBLIC OF NAMIBIA

MINISTRY OF AGRICULTURE, WATER & LAND REFORM

Serial Number	22/003	Agricultural Laboratory
Date	03/05/2022	Government Office Park, Windhoek
	Enquiries:	Soil Laboratory Tel: 2087752 or Mrs A Sipapo Tel: 2087073

Description of the methods we used for your soil analysis

SAMPLE PREPARATION	Soil samples are dried at a temperature not greater than 35 degrees C. The part of the sample retained on a 2 mm sieve, called the fine earth fraction, is used for analysis. The fraction >2mm is referred to as stones and gravel.
AVAILABLE PHOSPHORUS	Ohlsen method: Extraction with sodium bicarbonate. Phosphate measured spectrophotometrically using the phosphomolybdate blue method.
EXTRACTABLE CATIONS (AVAILABLE K,Mg,Ca)	Extraction with 1M ammonium acetate at pH 7. Measurement of calcium, magnesium, potassium and sodium by Inductively coulped plasma(ICP).
EXCHANGEABLE CATIONS & CATION EXCHANGE CAPACITY(CEC)	Extraction with 1M ammonium acetate at pH 7 if pH(H2O)<6.8 & EC<0.4 mS/cm. Extraction with 50:50 ammonium acetate (1M) and ethanol at pH 7 if pH(H2O)>6.8 & EC>0.4mS/cm. Calcium, magnesium, sodium and potassium measured by Inductively coulped plasma(ICP).
TEXTURE and PARTICLE SIZE ANALYSIS (SAND, SILT and CLAY)	Dispersion of soil with sodium hexametaphosphate/sodium carbonate. Determination of silt and clay by pipette method. Sand fraction determined by sieving to retain >53 micron fraction. Textural Class using the USDA classification system.
ORGANIC CARBON (ORGANIC MATTER CONTENT)	Walkley-Black method (sulphuric acid-potassium dichromate oxidation). A factor is included in calculations to take account of incomplete oxidation. Organic matter content calculated as organic-C x 1.74.
ORGANIC MATTER (by loss on ignition)	Organic matter is estimated by measuring the weight loss when dried samples are heated in a muffle furnace at 360 degrees C for 4 hours.
pH (KCl)	Measured in a 1:2.5 soil : IM potassium chloride ratio suspension on a mass to volume basis.
pH(water)	Measured in a 1:2.5 soil : water ratio suspension on a mass to volume basis.
ELECTRICAL CONDUCTIVITY (SOLUBLE SALT CONTENT)	Measurment in the supernatant of the 1:2.5 soil:water suspension prior to measurement of pH. Units of measuremnt are mS/cm (1 mS=1000 uS). High results indicating possible salinity hazard are repeated on the extract of a saturated soil paste.
TOTAL NITROGEN	The sample is then introduced to the furnace containing only pure oxygen, resulting in a rapid and complete combustion(oxidation). Nitrogen present are oxidized to NOx respectively. The NOx gases are passed through a reduction tube filled with copper to reduce the gases to N and onto a thermal conductivity cell(TC) utilized to detect the N2.
EXTRACTABLE ACIDITY	Extraction with 1M KCl and titration of extract to determine acidity.
CARBONATE (as Calcium Carbonate)	Reaction of soil with hydrochloric acid and estimation of acid consumed by titration with sodium hydroxide.
CARBONATE (estimation)	Treatment of dry soil with 10% hydrochloric acid and observation of effervescence.
AVAILABLE SULPHUR (as SULPHATE)	1:2 weight:volume extraction of soil with 0.01M calcium chloride. Sulphate-S estimated by measuring turbidity at 600 nm following treatment with acidified barium chloride.
SULPHATE (estimation)	Soil:water extract from pH/EC measurement made 0.01M with respect to calcium by addition of 1M calcium chloride. Filtered extract reacted with acid barium chloride and turbidity visually compared with standard solution of sulphate-S.
SALINITY ANALYSIS	Saturated soil:water paste prepared and the extract recovered by vacuum filtration. Anions and cations are measured in the extract. Sodium adsorption ration (SAR) is a diagnostic criterium for assessing salinity. It is equal to concentration of sodium divided by the sqaure root of one half the combined calcium and magnesium in the extract. All concentraions measured in me/l.
AVAILABLE MICRONUTRIENTS (Zinc, manganese, copper and iron)	Extraction with 0.5M ammonium acetate: 0.5M acetic acid: 0.02M EDTA at pH 4.65 at a 1:5 extraction ratio. Fe, Mn, Cu and Zn measured by Inductively Coupled Plasma(ICP). Available calcium, potassium and magnesium can also be measured in the extract.

Notes:	1 ppm (part per million) = 1 mg/kg = 1 ug/g
	1 % = 10 000 ppm