INVESTIGATION OF ECOSYSTEM SERVICES FOR MANAGEMENT OF CARBON STOCK IN PROTECTED AREAS: THE CASE OF AS SALEEL NATURE PARK RESERVE

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DECLRATION

I hereby declare that this thesis is the result of my own investigation and relentless efforts and the guidance of my supervisor, except where otherwise stated. The research was carried out at As Saleel Natural Park Reserve in Al Kamel Wa Al wafi , South of Sultanate of Oman under the supervision of Dr.Hameed Sulaiman , Biology Department , College of Science ,Sultan Qaboos University.

This Work has not been accepted for any degree, and is not being and not being concurrently submitted for any other degree.

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Signature:

ACKNOLEDGMENT

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Rabie

Investigation of Ecosystem Services for Management of Carbon Stock in Protected Areas:

The case of as Saleel Natural Park Reserve

ABSTRACT

Rabie Mohammed Said Al Rahbi

Thirty declared natural reserves of Sultanate of Oman covering approximately 15,000 km^2 are diversified into terrestrial and marine reserves. However, there is no appropriate information known on the potential environmental values of this protected areas. The main objective of the study is to generate information on ecosystem services, particularly carbon sequestration service in as Saleel natural park reserve, to provide the needed information for integrating them in management plans of natural reserves in Oman.

Understanding community perceptions of ecosystem services is crucial for effective conservation and sustainable resource management. A structured questionnaire survey comprising 89 responses was conducted to identify the community preferences for specific ecosystem services and awareness of protected areas. The findings highlight significant patterns in awareness of the term protected area, with the majority of respondents demonstrating a high level of awareness regarding protected areas (91.01%). In terms of attitudes toward conservation, the majority of respondents (96.6%) agreed that it is important to preserve plants and animals, while only 3.37% disagreed. This strong consensus reflects widespread support for conservation efforts. The correlation analysis showed weak relationships among the ecosystem services, with most values close to zero. However, a moderate positive correlation between direct benefits like food for animals and timber services, and soil regulations and recreational services.

A limited number of biomass models for accurately predicting the biomass of dominant tree species limit reliable estimates of carbon stocks in drylands. In this study a total of 45 *Vachellia tortilis* were measured for biometric variables (diameter at stump height (DSH), tree height (H) and crown area diameter) inside the reserve. Twenty trees from same species with a diameter at stump height (DSH) ranging from 18.5 cm to 150 cm were selected for destructive sampling for biomass prediction and carbon stock estimation. Linear multiple regression analysis was done using SPSS software between the 3 variables, DSH, H, CrA (x) and the total dry biomass (y). Five models were developed and all of them tested for the best fit model based on R-Square and Mean Square Error (MSE). Model 5 was the most accurate model including LOG of DSH and LOG of CrA (R^2 =0.97, MSE=0.114). The models developed in this research fills critical gap in

estimating AGB of terrestrial native species in dry lands in Oman and other countries with similar ecological and climate condition.

In situ measurement of *Vachellia tortilis* was done to estimate the above and belowground biomass and carbon stock in 0.980 km^2 in the reserve. The field measurement was carried out in three transects each with a total of ten circular plots with a 15 m radius. A total of 314 trees were recorded and the circumference at stump height was measured (at 0.3m above the ground), where the biomass was estimated using the allometric equations. The total mean aboveground biomass and belowground biomass were estimated in Transects 1,2 and 3 to be 21.6, 28, 46.6 kg/m^2. respectively. The total carbon stock and CO_2 sequestered were about 10.8,14 and 23.3 kg/m^2 respectively. The Total CO_2 sequestration equivalent in the study area is about 0.177 tons.

Additionally, soil moisture and carbon content were measured to assess the environmental condition of the study area. Soil samples were collected from 30 plots within 0.980 km^2, at a depth of 0-15 cm and a reference sample was taken from outside the reserve. Most plots in the middle of the study area had the lowest soil moisture content, indicating varying environmental conditions across the area. Soil carbon content was determined using the Walkley-Black method by titration. Plots located on the edges of the study area in Transects 1 and 3 had the lowest carbon contents, reflecting the variation in soil conditions across the study area.

Lastly remote sensing technique was employed to assess the vegetation health in the reserve through maximum likelihood object-based classification method. The *Vachellia tortilis* healthiness status were identified using Normalized Difference Vegetation Index (NDVI). The results showed that the *Vachellia tortilis* forest in the reserve area is ranging from moderate to good but majority of them are in moderate condition. The results showed that, they are in moderate state giving NDVI values between 0.3 to 0.59, where about 40% are in a good status giving NDVI values between 0.6 to 0.99. Therefore, the study recommends that Al Saleel Natural Park as protected area should continue and conservation plans should be strengthened to minimize the impact of human activities and environmental factors on the reserve.

دراسة خدمات النظم البيئية لإدارة مخزون الكربون في المناطق المحمية: حالة محمية حديقة السليل الطبيعية

الخلاصة

توجدإحدى وثلاثون محمية طبيعية مُعلنة في سلطنة عُمان، تغطي مساحة تُقارب 15,000 كيلومتر مربع، مُتنوعة بين محميات برية وبحرية. ومع ذلك، لا تتوفر معلومات كافية عن القيم ,والفوائد البيئية لهذه المناطق المحمية. الهدف الرئيسي من هذه الدراسة هو جمع معلومات حول خدمات النظم البيئية ، وخاصةً خدمة عزل الكربون في محمية حديقة السليل الطبيعية، لتوفير المعلومات اللازمة لإدماجها في خطط إدارة المحميات الطبيعية في سلطنة عُمان.

إن فهم تصورات المجتمع لخدمات النظم البيئية أمر بالغ الأهمية للحفاظ الفعَال والإدارة المستدامة للموارد. وقد أُجري استبيان منظم شمل 89 إجابة لتحديد تفضيل المجتمع لخدمات النظم البيئية المحددة ومدى الوعي بالمناطق المحمية. وقد أوضحت النتائج أنماطًا مهمة في الوعي بمصطلح المنطقة المحمية، حيث أظهر غالبية المجيبين للإستبيان مستوى عالٍ من الوعي بشأن المناطق المحمية (91.01%). وفيما يتعلق بالمواقف تجاه الحفاظ على البيئة، اتفق غالبية المجيبين (96.6%) على أهمية الحفاظ على النباتات والحيوانات، بينما لم يوافق على ذلك سوى 3.37%. ويعكس هذا الإجماع القوي دعمًا واسع النطاق لجهود الحفاظ على البيئة.

أظهر التحليل الترابطي (الإحصائي) علاقات ضعيفة بين خدمات النظم البيئية حيث اقتربت معظم القيم من الصفر. ومع ذلك، كان هناك ارتباط إيجابي معتدل بين الفوائد البيئية المباشرة مثل الغذاء للحيوانات وخدمات الأخشاب، وبين تعزيز التربة والخدمات الترفيهية.

إن وجود عدد محدود من معادلات احتساب الكتلة الحيوية المُستخدمة للتنبؤ الدقيق بالكتلة الحيوية لأنواع الأشجار السائدة ، يقلل من موثوقية تقديرات مخزون الكربون في الأراضي الجافة. وفي هذه الدراسة، تم أخذ قياسات للمتغيرات الحيوية وهي قطر الجذع وارتفاع الشجرة وقطر مساحة التاج لعدد.45 شجرة من نوع أشجار السمر داخل المحمية . اختيرت عشرون شجرة من نفس النوع، يتراوح قطرها عند ارتفاع الجذع بين 18.5 سم و150 سم، لأخذ عينات منها للتنبؤ بالكتلة الحيوية وتقدير مخزون الكربون. أُجري تحليل الانحدار المتعدد الخطي باستخدام برنامج SPSS بين المتغيرات الثلاثة: وهي قطر الجذع وارتفاع الشجرة وقطر مساحة التاج ، وإجمالي الكتلة الحيوية الجافة .

طُوِّرت خمسة معادلات، واختُبرت جميعها لتحديد أفضل معادلة ملائمة في تقدير الكتلة الحيوية لأشجار السمروإحتساب مخزون الكربون بناءً على معامل التحديد الإحصائي ومتوسط خطأ التربيع .كانت المعادلة الخامسة الأكثر دقة،(معامل التحديد =0.97 ، ومتوسط الخطأ =0.0114).

تُسهم المعادلات المُطوّرة في هذا البحث لسد الفجوة الحرجة في تقدير الكتلة الحيوية العلوية للأنواع البرية المحلية في الأراضي الجافة في سلطنة عُمان ودول أخرى ذات ظروف بيئية ومناخية مماثلة.

تم أخذ القياسات لعدد من أشجار السمر في منطقة الدراسة لتقدير الكتلة الحيوية ومخزون الكربون فوق وتحت الأرض في مساحة 0.980 كيلو متر مربع في المحمية. وتم إجراء القياسات الميدانية في ثلاثة خطوط عرضية، كل منها بإجمالي عشر قطع دائرية بنصف قطر 15 مترًا. تم تسجيل ما مجموعه 314 شجرة وتم قياس محيط ارتفاع الجذع لها (عند 0.3 متر فوق سطح الأرض)، حيث تم تقدير الكتلة الحيوية باستخدام معادلة موجودة. تم تقدير متوسط الكتلة الحيوية الكلية فوق الأرض والكتلة الحيوية تحت الأرض في القطاعات العرضية 1 و2 و3 21.6 و28 و46.6 كجم/متر مربع على التوالي. بلغ إجمالي مخزون الكربون وثاني أكسيد الكربون المعزول حوالي 10.8 و14 و23.3 كجم/متر مربع على التوالي. يبلغ مكافئ عزل ثاني أكسيد الكربون الكلي في منطقة الدراسة حوالي 0.177 طن.

بالإضافة إلى ذلك، تم قياس رطوبة التربة ومحتوى الكربون فيها لتقييم الحالة البيئية لمنطقة الدراسة. جُمعت عينات تربة من 30 قطعة دائرية ضمن مساحة 0.980 كيلومتر مربع، على عمق يتراوح بين 0 و15 سم، كما أُخذت عينة مرجعية من خارج المحمية. سجلت معظم العينات الواقعة في منتصف منطقة الدراسة أقل نسبة رطوبة في التربة، مما يشير إلى تباين الظروف البيئية في جميع أنحاء المنطقة. حُدد محتوى الكربون في التربة باستخدام طريقة ووكلي-بلاك بالمعايرة. سجلت العينات الواقعة على أطراف منطقة الدراسة في المقطعين 1 و3 أقل نسبة كربون، مما يعكس تباين ظروف التربة في جميع أنحاء منطقة الدراسة.

وأخيرًا، استُخدمت تقنية الاستشعار عن بُعد لتقييم حالة اخضرار الغطاء النباتي في المحمية من خلال أسلوب التصنيف القائم على الكائنات ذي الاحتمالية القصوى. وتم تحديد حالة اخضرار غابات أشجار السمر بإستخدام مؤشر الفرق الطبيعي للغطاء النباتي .وأظهرت النتائج أن حالة اخضرار غابات أشجار السمر في منطقة المحمية تتراوح بين المتوسطة والجيدة، إلا أن معظمها في حالة متوسطة. حيث أظهرت نتائج حالة الإخضرار المتوسطة قيما لمؤشر الفرق الطبيعي للغطاء النباتي بين 0.3 و0.59، بينما تراوحت القيم لحوالي 40% من غابات أشجار السمر بين 0.6 و0.99. ولذلك، توصي الدراسة باستمرار حديقة السليل الطبيعية كمنطقة محمية، وتعزيز خطط المحافظة عليها للحد من تأثير الأنشطة البشرية والعوامل البيئية.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AGB	Above Ground Biomass
ASTM	American Society for Testing and Materials
BGB	Below Ground Biomass
CrA	Crown Area
DSH	Dimeter at Stump Height
EA	Environment Authority
ESs	Ecosystem Services
GIS	Global Information System
GPS	Global Positioning System
H	Height
IUCN	International Union for Conservation of Nature
MA	Millennium Ecosystem Assessment
NDVI	Normalized Difference Vegetation Index
NP	National Parks
PAs	Protected Areas
ROI	Region of Interest
RS	Remote Sensing
SEM	Structural Equation Model
SNPR	Saleel Nature Park Reserve
SOC	Soil Organic Carbon

APPENDICES

CHAPTER.1 INTRODUCTION

1.1 Background of the Study

Oman, characterized by its varied ecosystems that include deserts, mountains, coastal areas, and wetlands, serves as a distinctive subject for the examination of ecosystem conservation and the provision of ecosystem services. The country has created an extensive network of more than 31 protected areas by Royal Decrees and Ministerial Decisions, designed to preserve its natural heritage. These areas encompass marine reserves, desert parks, mountainous protected areas, and wetland conservation zones, each targeting the distinct ecological issues of the area. In the past and the present the conservation efforts are targeted towards popular species particularly animals such as the Arabian oryx, green sea turtles, and Arabian gazelles. In addition to safeguarding these species, protected areas in Oman offer many ecological services that benefit local residents, including food and water supplies, flood mitigation, and recreational opportunities. Understanding the significance of these services and the perceptions of local communities towards them is essential for effective conservation and management efforts. Effective management of protected areas in Oman necessitates a balance between biodiversity conservation and the livelihoods of adjacent communities.(Muscat Daily, 19th April,2025)

This research investigates the significance of key species, including *Vachellia tortilis* (formerly *Acacia tortilis*), recognized for its ecological roles in habitat provision, soil stabilization, and carbon sequestration. These species are crucial in arid regions, characterized by little vegetation and a heightened susceptibility to ecosystem instability. This research also seeks to quantify the impact of *Vachellia tortilis* in mitigating climate change and sustaining ecosystem services in Oman's protected areas by constructing allometric equations and evaluating its carbon sequestration potential.

The correlation between soil moisture and the health of vegetation, especially for species suited to arid environments, offers significant insights into the resilience of ecosystems amid climate change. Remote sensing technologies, including NDVI, provide a novel method for monitoring and evaluating vegetative health and carbon sequestration in extensive protected areas, hence enhancing management and conservation efforts (Al Mulla *et al* ., 2022)

This project seeks to integrate scientific information, conservation initiatives, and community perspectives to improve the sustainable management of protected areas in Oman. Moreover, this research will enhance the comprehensive understanding of how these sectors might promote environmental and socio-economic sustainability in dry environments.

1.2 Protected areas in Oman

Protected areas are vital for conserving biodiversity, alleviating climate change, and sustaining critical ecosystem services in terrestrial and marine ecosystems. These areas are acknowledged worldwide as essential for conserving endangered species, preserving natural resources, and offering advantages including water purification, soil stabilization, and carbon sequestration. In arid and semi-arid regions, where ecosystems are especially susceptible to climate change and human activity (IUCN, 2021)

Oman had designated 30 protected places via Royal Decrees, which include natural reserves, national parks, and protected landscapes. These locations function as essential sanctuaries for endangered species, crucial habitats, and ecologically important regions. The creation and administration of these reserves are regulated by the Law on Nature Reserves and Wildlife Conservation, enacted by Royal Decree No. 6/2003. Oman’s protected areas are allocated over its many geographies, encompassing maritime, desert, mountainous, and wetland habitats.

They are essential for safeguarding Oman’s natural legacy, facilitating the conservation of its abundant biodiversity and delicate ecosystems. By December 2024,

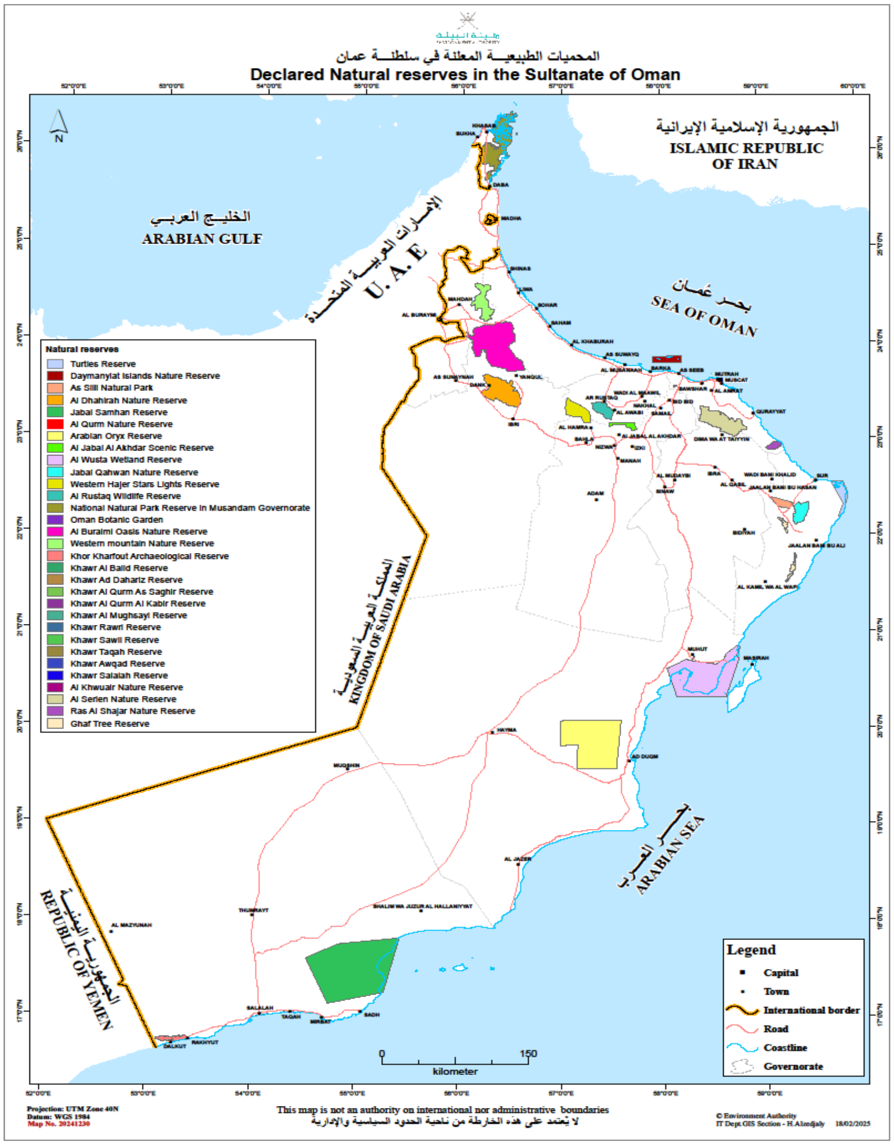


Figure.1. Protected Areas in Oman (EA ,GIS department ,2024)

Prominent instances comprise: Al Jabal Al Gharbi Natural Reserve: Instituted by Royal Decree No. 23/2024, this reserve safeguards the distinctive flora and fauna of the Al Jabal Al Gharbi region. Al Dhahirah Nature Reserve: Established by Royal Decree No. 24/2024, this reserve aims to conserve the natural heritage of the Al Dhahirah governorate Wahat Al Buraimi Nature Reserve: Established by Royal Decree No. 25/2024, it preserves the oasis ecosystems of the Buraimi region (EA, 2020).The Natural National Park Reserve in Musandam was established by Royal Decree No. 54/2022 to safeguard the distinctive biodiversity of the Musandam region. Additional notable reserves comprise the Daymaniyat Islands Nature Reserve, Ras Al Jinz Turtle Reserve, and Jabal Samhan Nature Reserve. These areas not only safeguard wildlife but also promote sustainable tourism, environmental education, and scientific researches. Oman's dedication to environmental conservation is demonstrated through these initiatives, safeguarding its habitats nationally while conforming to global environmental objectives. These protected areas are essential for conservation, sustainable tourism, and environmental research, safeguarding Oman's rich natural heritage for future generations.

1.3 Ecosystem Services and Their Significance

According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019 Global Assessment Report, the term "ecosystem services" has been largely replaced by the broader and more inclusive concept of "nature's contributions to people (NCP)". The IPBES assessment which was done on 2019 define Ecosystem services as "Nature's contributions to people (NCP)" are all the contributions, both positive and negative, of living nature (i.e., diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life for people. (IPBES,2019)

This includes what was traditionally referred to as ecosystem services, but also includes non-material contributions (such as cultural identity and spiritual significance) and recognizes diverse worldviews, including indigenous and local knowledge systems. (IPBES, 2019). In dry and semi-arid regions, protected areas frequently include distinctive and delicate ecosystems essential for biodiversity preservation and ecosystem stability. The understanding of ecosystem services by local communities is essential for effective conservation and management efforts. Communities next to protected areas are directly influenced by the health and functionality of these ecosystems. Comprehending community perceptions and valuations of ecosystem services helps guide policies and management approaches that correspond with local requirements. Prior research indicates that local attitudes might differ markedly according to socioeconomic conditions, cultural values, and reliance on natural resources (Barton *et al.,* 2012; Doxford *et al.,* 2020). Evaluating community perceptions facilitates the connection between conservation initiatives and local circumstances, fostering sustainable management practices.

1.4 *Vachellia tortilis* in Arid Environments

Vachellia tortilis (formerly *Acacia tortilis*) is a crucial tree species in dry and semi-arid habitats, offering significant ecological functions including wildlife habitat, soil stabilization, and nutrient cycling.

Allometric equations, which connect tree dimensions to biomass and other structural characteristics, are crucial for evaluating the ecological function and carbon sequestration potential of *Vachellia tortilis* in these ecosystems. Formulating precise allometric equations for this species is essential for enhancing understanding of its role in ecosystem services and for guiding management strategies intended to safeguard its ecological functions (Haggar *et al.*, 2015).

1.5 The Role of *Vachellia tortilis* in Carbon Sequestration

Carbon sequestration is the process by which trees and other vegetation absorb and store atmospheric carbon dioxide, thereby alleviating the impacts of climate change. In dry areas characterized by limited vegetation and slow development rates, the contribution of trees such as *Vachellia tortilis* to carbon sequestration is notably important. Comprehending the carbon sequestration capacity of *Vachellia tortilis* aids in evaluating its role in global carbon cycles and formulating ways to augment carbon storage in dry environments (Sommerville *et al.,* 2016 , Al Ismaili *et al* ., 2024). This knowledge is crucial for amalgamating conservation and climate change mitigation initiatives.

1.6 Dynamics of Soil Moisture in Arid Environments

Soil moisture is a vital determinant affecting the growth and vitality of vegetation, particularly in arid regions where water resources are few. *Vachellia tortilis,* acclimated to arid environments, depends on soil moisture for its sustenance and development. Investigating the correlation between soil moisture and *Vachellia tortilis* can yield critical insights into the species' hydric needs, adaptive mechanisms, and ecological significance. This knowledge is crucial for managing water resources, forecasting the effects of climate change on vegetation, and formulating policies for sustainable land use in arid places (yadeta *et al*., 2018).

1.7 Remote Sensing for Vegetation Monitoring

Remote sensing technologies provide effective instruments for monitoring and evaluating vegetation in protected regions. Methods like satellite imaging and aerial surveys facilitate the assessment of vegetation health, distribution, and temporal changes. The Normalized Difference Vegetation Index (NDVI) is a widely utilized indicator in remote sensing that offers insights into vegetation coverage and productivity. NDVI measurements serve to evaluate vegetation health, monitor land cover alterations, and guide conservation initiatives. The application of remote sensing to monitor vegetation in protected areas, such as *Vachellia tortilis*, improves the management and protection of these ecosystems (Huete *et al.,* 2002).

2. Statement of Problem

Oman has presently designated more than 30 protected areas. There is a lack of scientific and precise data regarding the types of ecosystem services and their status within the reserve. Furthermore, limited studies have been conducted to evaluate the ecological values of those protected regions. There is no informational database regarding the perceptions of resident communities on protected areas concerning ecosystem services and their interrelationship with the system. There are Insufficient data regarding the carbon sequestration potential of certain dominating species. Also, there are no attempt by researchers to develop a specific allometric equations in Oman and the region for estimation of biomass and carbon sequestration potential of dominant species such as *Vachellia tortilis* in conservation areas.

3. Justification and Research Contribution

This study seeks to amalgamate several elements of ecosystem services, community views, and ecological evaluations within protected regions. This research tackles significant gaps in understanding the ecological roles of *Vachellia tortilis* in arid environments by creating allometric equations, assessing its carbon sequestration potential, and examining soil moisture dynamics. Furthermore, integrating community opinions and employing remote sensing technologies offers a holistic strategy for conservation and management. The results of this study are anticipated to improve conservation methods and national conservations strategies, deepen our comprehension of ecosystem services, and bolster sustainable management practices in protected areas.

4. Objectives of the Research

Main objective

To investigate ecosystem services in as Saleel Natural Park Reserve and assess their role in carbon management, integrating community perceptions, ecological modeling, and remote sensing techniques to enhance conservation strategies.

Specific objectives

1. To develop Site specific –species algometric equation (models) for biomass estimation of *Vachellia tortilis based* on field measurement & statistical modelling.

2. To quantify carbon sequestration potential of *Vachellia tortilis* using field measurement & existing allometeric equation.

3.To Estimate the soil carbon and moisture level in the study area.

4. To evaluate the effectiveness of NDVI and remote sensing techniques in monitoring vegetation health of *Vachellia tortilis* in as Saleel Nature Park reserve

5. To identify key ecosystem services and assess community awareness & preferences using questionnaire and statistical models analysis

5.Hypothesis

A hypothesis test was formulated to assess the significance of the relationships between biomass and the variables with the strongest correlations. The null hypothesis (H0) posited that the regression coefficients for biomass, DSH, and CA were equal to zero, while the alternative hypothesis (H1) posited that at least one of these coefficients was not equal to zero.

We tested multiple models with different combinations of the predictor variables and transformations, including:

- Model A: DSH, CA, with constant = 0
- Model B: DSH, CA, with constant ≠ 0

- Model C: DSH only, with constant = 0
- Model D: log-transformed DSH
- Model E: log-transformed DSH and log-transformed CA, with constant = 0

6. Significance of the research

This research study aims to identify and assess ecosystem services in Al Saleel Nature Park Reserve. It is the first work to understand the value of an ecosystem of one of the important natural protected area in Oman. Moreover, it will help to give the decision makers a clear and scientific information about the importance of integrating ecosystem services concept into planning and conservation strategies of protected areas. On the other hand, also helps to identify the relationship between the community and their surrounding environment. Also, the study identified the factors the government must take into consideration when preparing conservation and management plans for nature reserves.

In addition to that, specifically the study focused on the importance of the most dominant plant species in the area (*Vachellia tortilis*) and its significance to climate regulation in the study area by estimating above and below carbon and soil carbon stock and studying the one of the important environmental factors, namely soil moisture in the reserve. The study developed a first allometric equation in Oman and the whole region for estimating carbon sequestration in native species *Vachellia tortilis* in arid areas. Also, the study will be an entry point for an effective management of the natural resources in protected areas to give information for management purpose helping decision makers to give conservation priorities to ecosystem services which is important for the society in the long run.

7. Limitations of the research

1- There were difficulties in accessing the study area, as obtaining the necessary permits took a significant amount of time, and these permits required periodic renewal, which delayed the research process.

2- A limited number of destructive samples were harvested due to restrictions on cutting trees in and around protected areas in Oman. This constraint hindered the collection of comprehensive data on tree biomass and carbon sequestration.

3- The reserve covered an extensive area of approximately 220 km², making it challenging to cover the entire area comprehensively. Limited resources and manpower further constrained the ability to gather data across the full extent of the reserve.

4- The study was conducted in a very dry and arid region, where temperatures often exceeded 50°C. These extreme conditions made fieldwork difficult and physically demanding, limiting the amount of time that could be spent collecting data in the study area.

5- There were not enough human resources available for the destructive sampling, which led to the decision to limit the study to establishing aboveground biomass (AGB) models only. This limitation prevented a more detailed assessment of other ecological parameters.

6- The communities residing inside the reserve are few in number, and most of them were not comfortable participating in interviews. This limited the scope of gathering local perceptions and community-based data for the study and factors affecting ESs strength or weakness was not expressed deeply in the study because of limited data.

8. Structure of the Thesis

The thesis is structured as follows: **Chapter 1:** Introduction – Provides an overview of the background, problem statement, justification & research contribution, objectives, significance of the research, limitation of the research and structure of the thesis. **Chapter 2:** Literature Review - Reviews existing research and theoretical frameworks related to research scope **Chapter 3**: Study Area & Methodologies: Describe the study area and its climatic conditions and its features and describes the research design, data collection methods, and analysis techniques used in the study. **Chapter 4:** Results & Discussions - Presents the findings of the research, including data analysis and interpretation and discusses the implications of the findings, compares them with existing literature, and explores their relevance to the research problem. **Chapter 5:** Summary and Conclusion – Summarizes the key findings, provides recommendations for practice and future research, and concludes the study. **References -** Lists all sources cited in the thesis. **Appendices -** Includes supplementary materials such as raw data, questionnaires, and additional documentation.

CHAPTER.2 LITRATURE REVIEW

The literature review chapter forms the foundation of my research by examining existing studies and scientific advancements related to the key objectives of this thesis. It explores the development of site-specific allometric equations, the estimation of carbon sequestration, the estimation of soil moisture, and the mapping of environmental changes and NDVI calculations, with a specific focus on *Vachellia tortilis* (formerly *Acacia tortilis*) in arid nature reserves. This chapter aims to synthesize current knowledge, identify gaps, and highlight methodological approaches.

2.1. Introduction to allometric equations in biomass measurement

Allometric equations are fundamental tools in estimating tree biomass non-destructively by correlating easily measurable parameters, like trunk diameter and height, with total biomass. These equations are species-specific or ecosystem-specific due to variability in tree form, density, and growth patterns. For Acacia species, especially in arid and semi-arid regions, several allometric models have been developed to improve the accuracy of biomass and carbon stock assessments (Gibbs *et al.,* 2007). The significance of refining these equations lies in Acacia's role in both ecosystem stability and carbon sequestration in challenging climates, where environmental pressures make direct biomass measurement difficult.

2.2. Common Allometric Equations for Acacia Biomass estimation

Several allometric equations have been developed specifically for Acacia species, each designed to suit distinct environmental conditions and forest structures. Most equations incorporate variables like diameter at breast height (DBH), tree height, and sometimes wood density. These are calibrated for arid and semi-arid ecosystems, which often contain sparse tree cover and low biomass per tree, compared to more humid forests. Examples include:

Chidumayo (2013) developed equations for semi-arid African woodlands, using DBH and height as primary predictor of aboveground biomass, which have been effectively applied to Acacia species in African savannas. **Sileshi (2014)** compiled a comprehensive review of biomass equations specifically for

African tree species, providing species-specific models that account for wood density variations, which is especially relevant for multi-stemmed Acacia trees common in dryland ecosystems. Recent studies on biomass measurement in Acacia species have focused on refining and validating allometric equations to enhance accuracy. These studies are crucial for adapting models to specific Acacia populations, as biomass allocation patterns can vary significantly among species and locations. **Mokany *et al*., (2006)** examined root-to-shoot ratios in global dryland ecosystems and found that Acacia species allocate approximately 40-50% of total biomass to roots. This research informs the design of allometric models that factor in belowground biomass, which is often underrepresented in biomass assessments.

Lahive *et al*., (2021) studied the application of allometric equations for biomass estimation in mixed savanna ecosystems, emphasizing the importance of calibration for multi-stemmed species like *Vachellia tortilis*. This study found that models incorporating both stem number and DBH were more accurate in estimating biomass than DBH alone. **Colgan *et al*., (2013)** utilized LiDAR technology to supplement traditional allometric equations for Acacia species in southern African savannas. This approach enabled more precise measurements by capturing complex canopy structures, an innovation especially useful for multi-stemmed Acacia varieties. **Muukkonen & Heiskanen (2007)** provided an extensive review of biomass equations for various African tree species, highlighting the challenges of applying generalized equations to arid ecosystems where tree morphology deviates significantly from tropical species. This study has implications for Acacia biomass estimation, as it underscores the need for localized calibration.

2.3. Mechanisms of Carbon Storage in Arid Ecosystems

In arid ecosystems, carbon storage mechanisms differ from those in temperate regions due to extreme environmental factors like limited precipitation, high temperatures, and nutrient-scarce soils. Carbon is often stored within soil organic matter and belowground biomass rather than aboveground biomass, as water limitations restrict growth. Some species, however, is adapted to these conditions with specific traits that allow for efficient water and nutrient use, which facilitates greater carbon sequestration capacity (Davis & Chen, 2020). Its extensive root system plays a central role in this process, allowing the plant to access deeper soil layers for water and to store carbon in subsoil regions where it remains protected from erosion and decomposition.

Martinez *et al. (2022*) observed that *Vachellia tortilis* contributes to soil organic carbon (SOC) accumulation through leaf litter and root exudates, enriching the soil with organic matter. This process has been particularly effective in nature reserves, where human impact is minimized, and natural growth

processes remain uninterrupted. Additionally, symbiotic nitrogen-fixing bacteria associated with *Vachellia tortilis* roots further enhance soil fertility, creating a favorable environment for carbon sequestration by promoting soil health and stability.

2.4. Carbon Sequestration Potential of *Vachellia tortilis*

2.4.1. Role of Acacia species in carbon sequestration: a focus on biomass and soil carbon.

The carbon sequestration potential of *Vachellia tortilis* lies in both its aboveground biomass and its significant contribution to soil organic carbon (SOC). Several studies emphasize the species' role in biomass accumulation due to its relatively fast growth rate compared to other arid-region flora, particularly in regions with limited precipitation. For instance, Brown *et al*. (2023) found that in controlled conditions, *Vachellia tortilis* can increase its biomass by up to 15% under optimal soil moisture conditions, making it a viable species for arid-land reforestation and afforestation projects aimed at sequestering carbon.

2.4.2. Adaptations of *Vachellia tortilis* to arid climates, enhancing resilience and potential carbon stock.

The species has a deep root system that not only supports survival in drought conditions but also enables carbon storage in subsoil layers. This deep carbon sequestration is particularly valuable in arid environments, where surface carbon is vulnerable to degradation and erosion. Lin and Shukla (2021), highlighted that in African arid zones, *Vachellia tortilis* contributes significantly to carbon storage by depositing organic matter deep within the soil, which has been shown to persist longer compared to surface carbon deposits, which are often subject to disturbance.

2.4.3. Importance of *Vachellia tortilis* in Biomass Measurement Studies

Acacia species, such as *Vachellia tortilis,* exhibit unique growth patterns adapted to arid and semi-arid conditions, which influence their biomass distribution. Research indicates that these trees allocate substantial biomass to roots, a key trait for survival in arid environments but one that complicates biomass estimation. Given their ecological roles, accurate biomass measurements are critical for estimating carbon stocks in arid and semi-arid ecosystems, particularly within protected areas, which are essential carbon sinks in desert landscapes (Henry *et al.*, 2011).

2.4.4. Potential benefits and roles Acacia species in ecosystem-based climate adaptation strategies

Vachellia tortilis plays an essential role in climate adaptation and mitigation, particularly in regions susceptible to desertification. Its capacity to stabilize soil, reduce erosion, and provide shade contributes to microclimate regulation within arid landscapes. By increasing vegetation cover, *Vachellia tortilis* also supports biodiversity, which is essential for maintaining resilient ecosystems under climate stressors (Nguyen & Lee, 2023). Additionally, the species is widely incorporated into ecosystem-based adaptation projects aimed at creating sustainable landscapes that can withstand climate change impacts. In these projects, *Vachellia tortilis* is used to rehabilitate degraded lands, increase soil organic carbon, and improve water retention in soils. Santos et al. (2022) noted that the presence of *Vachellia tortilis* in protected areas not only enhances carbon sequestration but also supports a range of ecological services critical for long-term climate resilience.

2.5. Methodologies for Measuring Carbon Sequestration in *Vachellia tortilis*

Various methodologies are employed to measure carbon sequestration in *Vachellia tortilis*, ranging from traditional biomass measurement techniques to advanced remote sensing technologies. Biomass estimation is typically conducted through allometric equations, which relate tree diameter, height, and wood density to calculate total biomass. These equations have been developed specifically for arid-adapted species like *Vachellia tortilis*, where factors like trunk diameter can significantly influence the accuracy of carbon stock assessments (Garcia & Thompson, 2020).

Roxburgh ***et al,***. (**2015**) recommend collecting between 17 and 95 individuals to achieve biomass predictions with a standard deviation. In this research we took 20 trees within a 25-meter buffer zone around the proposed gas pipeline route were identified and marked. The trees were categorized based on a post-classification that was done, ensuring that only the designated trees were included in the study.

Soil sampling remains essential for belowground carbon measurement, as soil organic carbon represents a major component of sequestration in arid regions. Stratified random sampling is often employed to capture SOC variability across different depths and locations. Innovations in soil sampling methods, including core sampling and isotope analysis, have improved the precision of SOC estimates, facilitating better understanding of carbon dynamics at various soil depths. (Spertus,2021).

2.6. Impact of Environmental Factors on Carbon Storage of *Vachellia tortilis* in arid environment

Carbon sequestration potential in *Vachellia tortilis* is influenced by a range of environmental variables, including soil type, water availability, temperature, and land management practices. In areas with higher soil moisture, *Vachellia tortilis* shows increased biomass production, which directly correlates with greater carbon storage (Li *et al*., 2023). However, in areas with extreme drought, biomass accumulation may be limited, although belowground carbon storage remains relatively stable due to the species' deep-rooting nature.

Protected areas such as national parks and reserves generally offer more favorable conditions for carbon sequestration compared to unprotected regions. Reduced soil erosion, minimal grazing, and restrictions on human activity in these areas create a stable environment that fosters natural carbon storage processes. In a study on the impact of protection on carbon stocks, Yusuf and Singh (2021) found that *Vachellia tortilis* in fenced reserves showed 20% higher soil carbon levels than in adjacent unprotected areas. This disparity is attributed to the conservation of soil structure and the presence of mature trees that contribute to long-term carbon storage.

2.6.1. Determination of Soil Moisture and its dynamics with *Vachellia tortilis*

Soil moisture is a critical factor in arid environments, and *Vachellia tortilis* plays a role in modulating soil moisture levels:

Water Use Efficiency: *Vachellia tortilis* is known for its water-use efficiency. Its deep root system enables it to access groundwater, thereby impacting soil moisture dynamics. According to studies by Smit *et al*. (2021), this species can reduce soil moisture evaporation due to its canopy cover, which may lead to more stable soil moisture conditions beneath its canopy.

Soil Moisture and SOC Interaction: The interaction between soil moisture and SOC is complex. In arid environments, lower soil moisture can lead to reduced microbial activity and slower organic matter decomposition. However, *Vachellia tortilis* can buffer these effects by providing a more consistent microenvironment for soil microorganisms, thereby supporting higher SOC levels (Miller *et al*., 2020).

Impact on Soil Moisture Retention: Research by mureva *et al.* (2019) indicates that the presence of Vachellia tortilis can improve soil moisture retention due to its organic matter inputs, which enhance soil structure and porosity. This effect is particularly notable in protected areas where natural vegetation can help maintain soil moisture levels.

2.7. Remote Sensing in Arid and Semi-Arid Regions

Arid and semi-arid regions are characterized by limited water availability, extreme temperature fluctuations, and highly variable vegetation cover. These environmental challenges make ecological monitoring in these regions particularly difficult. Remote sensing plays a pivotal role in overcoming these challenges by offering a means to monitor vegetation dynamics, land cover changes, and soil conditions over large and often inaccessible landscapes. The application of remote sensing is especially important in detecting subtle changes in vegetation cover and degradation processes, which may otherwise go unnoticed due to the vastness of these regions (Dandois & Ellis, 2018; Liu & He, 2020).

2.7.1. Remote Sensing Applications for Ecosystem Services and Carbon Sequestration

The potential of remote sensing to contribute to the monitoring of ecosystem services, particularly carbon sequestration, has become increasingly important in the context of climate change mitigation. Carbon sequestration in arid and semi-arid ecosystems can play a significant role in reducing atmospheric CO2 levels, making it essential to estimate carbon stocks accurately. As discussed by Liu and Wang (2019), remote sensing can be used to estimate biomass and vegetation density, both of which are key parameters in determining carbon storage potential in these ecosystems.

Vegetation indices like NDVI are instrumental in assessing the health and productivity of ecosystems, which directly correlates with their capacity to sequester carbon. By tracking the growth and changes in vegetation cover over time, remote sensing allows for the estimation of carbon stocks and the identification of areas with high carbon sequestration potential (Zhang & Liu, 2019).

2.7.2. Land Cover Classification and Degradation Mapping

Land cover classification and change detection are essential applications of remote sensing in monitoring environmental degradation, especially in semi-arid and arid regions. Remote sensing provides high spatial and temporal resolution data that allows for the classification of land into various categories, such as vegetation, bare soil, and water bodies. Liu and Wang (2019) reviewed several methods for classifying land cover types in arid and semi-arid regions using satellite data, including supervised and unsupervised classification techniques. Supervised classification relies on known sample data (training data), whereas unsupervised classification clusters pixels into groups based on similar characteristics, without the need for predefined labels. These techniques are crucial for detecting changes in land cover over time, such as deforestation, desertification, or the encroachment of human settlements.

Classifications are particularly important in arid regions, where vegetation cover is sparse, and changes in land cover can be subtle yet significant. Satellite imagery with high spatial resolution, such as Landsat or Sentinel-2, provides the necessary detail to classify land cover types accurately and to detect degradation processes. Bastin *et al.*, (2019) demonstrated how remote sensing classifications help monitor tree cover and assess the extent of land degradation in semi-arid regions, which is vital for guiding conservation efforts and land restoration projects.

2.7.3. Vegetation Dynamics and Remote Sensing

Vegetation dynamics in arid and semi-arid regions are influenced by various factors, including precipitation, temperature fluctuations, and anthropogenic activities. Remote sensing enables the monitoring of vegetation cover, health, and productivity across time, thus providing valuable data on ecosystem responses to climate variability and land use changes (Tucker & Nicholson, 2020). One of the most widely used vegetation indices in remote sensing is the Normalized Difference Vegetation Index (NDVI), which quantifies vegetation density and health by analyzing the ratio between near-infrared (NIR) and red-light reflectance (Fensholt *et al.*, 2019). NDVI has proven to be effective in assessing vegetation dynamics in arid and semi-arid regions, as it captures the seasonal growth patterns and overall vegetation health (Liu & He, 2020).

NDVI values range from -1 to +1, with higher values indicating denser vegetation and lower values indicating sparse or degraded vegetation. In arid ecosystems, NDVI is particularly useful for tracking vegetation growth during the rainy season and detecting stress during drought periods (Zhang & Liu, 2019).

As discussed by Fensholt *et al.,* (2019), remote sensing techniques like NDVI calculations can help identify areas of land degradation and vegetation stress, which are crucial for understanding the impacts of climate change and land use on these fragile ecosystems.

classifications, researchers can differentiate between areas with significant vegetation biomass and those with low productivity, thereby refining carbon sequestration estimates. Bastin *et al*. (2019) also emphasized the importance of remote sensing in mapping tree cover extent in arid regions, which is vital for understanding the role of these ecosystems in global carbon cycling. The ability to track vegetation changes over large scales provides insights into the long-term trends in carbon storage, which is critical for making informed decisions about land management and conservation.

2.8. Identification & assessment of the ecosystem services provided by natural reserve

One of the primary objectives of this research is to understand how local communities perceive and interact with ecosystem services in the as Saleel natural park reserve. It aimed to identify and categorize the various ecosystem services provided by the reserve; provisioning, regulating, cultural, and supporting services, Examine the socio economic factors that affect the perception of the identified ecosystem within and the surroundings of the reserve, with some socio-economic factors and the proximity factor the surrounding community, employing both qualitative and quantitative methods (e.g., surveys, interviews,).

Through this approach, the study seeks to contribute to the understanding of the dynamics between biodiversity conservation, ecosystem service provision, and community well-being, offering policy-relevant recommendations for improving the management and governance of protected areas.

2.8.1. Introduction to Ecosystem Services

Ecosystem services (ES) refer to the benefits humans obtain from ecosystems, including goods (provisioning services) and services that support life and well-being (regulating, supporting, and cultural services). The concept of ecosystem services emerged from the need to recognize the integral role of ecosystems in supporting human societies (Daily, 1997). These services have been formalized in various frameworks, including the Millennium Ecosystem Assessment (MEA, 2005) and the TEEB report (The Economics of Ecosystems and Biodiversity, 2010).

Millennium Ecosystem Assessment (MEA, 2005) emphasizes the classification of services into four categories: provisioning, regulating, cultural, and supporting services. TEEB (2010) advocates for the economic valuation of ecosystem services to influence policy-making and highlight their significance in development. The MEA and other frameworks categorize ecosystem services into four major types: Provisioning services include products such as food, water, timber, and medicinal resources. Regulating services encompass climate regulation, water purification, and pollination. Cultural services involve non-material benefits like recreation, aesthetic value, and spiritual enrichment. Supporting services include processes like soil formation and nutrient cycling that underpin other services (Costanza *et al*., 1997). These services are vital for the well-being of both human societies and biodiversity.

2.8.2. Ecosystem Services in Protected Areas and National Parks

Protected areas (PAs) such as national parks are critical for conserving biodiversity and ensuring the continued flow of ecosystem services. These areas contribute to regulating services like climate regulation (e.g., forests acting as carbon sinks), and provisioning services like water and food (Schulze *et al*., 2015). PAs are considered a cornerstone of biodiversity conservation, serving as refuges for species and maintaining vital ecological functions (Naughton-Treves *et al*., 2005).

The conservation of biodiversity in PAs directly influences ecosystem service provision. Species-rich ecosystems often provide more stable and diverse services, particularly in areas such as pollination, water purification, and pest control (Barton *et al*., 2015; TEEB, 2010). By conserving biodiversity, protected areas enhance ecological resilience, which in turn ensures long-term service provision (Chazdon, 2008).Several studies have explored the provisioning and regulating services of protected areas. For example: **Karki *et al.* ,*(*2021)** assessed the carbon sequestration potential of forested protected areas in South Asia, demonstrating their critical role in offsetting regional carbon emissions and enhancing climate resilience. **Maes *et al.* ,*(*2012)** highlighted the role of European Natura 2000 sites in water purification and flood mitigation, showcasing the economic value of regulating services provided by these reserves. **Eldridge *et al.*, (2020)** studied arid rangelands and found that soil stabilization and erosion control were significantly higher within protected areas, particularly where sustainable grazing practices were implemented. Cultural and recreational services have also been studied in the national parks. For example; **Roux *et al*. (2020),** examined the tourism and educational value of South African national parks, linking well-managed ecosystem services to increased visitor satisfaction and revenue generation for conservation efforts. Also **Chan *et al.,(*2016)** emphasized the spiritual and cultural connections of indigenous communities to protected areas, advocating for the integration of traditional ecological knowledge in management practices.

However, significant gaps remain. Research is often limited to specific ecosystems, with a notable scarcity of studies in arid and semi-arid regions. Additionally, methodologies for valuing ecosystem services lack standardization, making cross-comparisons challenging. Studies like **De Groot *et al*. (2012)** have called for more integrative approaches, combining biophysical, economic, and cultural dimensions to provide holistic evaluations.

2.8.3. Management of Ecosystem Services in Protected Areas

The management of ecosystem services in PAs often requires integrating ecological science with social, economic, and governance considerations. Ecosystem-based management (EBM) is one approach that links the conservation of biodiversity with sustainable use of resources by local communities (McLeod *et al*., 2005). Co-management models, where local communities are involved in the governance of PAs, can increase the effectiveness of conservation efforts (Berkes, 2009).

2.8.4. Community Perceptions of Ecosystem Services

Community perceptions refer to how local populations understand and value ecosystem services, which may vary depending on socio-cultural, economic, and environmental contexts. These perceptions influence how communities interact with and manage natural resources (Tengö *et al.,* 2014). Understanding these perceptions is essential for integrating local knowledge into conservation planning (Noble *et al*., 2007).

Many studies have explored the role of local communities in valuing and managing ecosystem services. **Martín-López *et al.* (2019**) emphasized the importance of understanding cultural and spiritual ecosystem services in protected areas, noting that communities often value these intangible benefits more than provisioning or regulating services. **Shibia (2018)** conducted a study in Kenya's Amboseli National Park, revealing that communities living near the park recognized its contributions to water availability, livestock grazing, and ecotourism income but expressed concerns about wildlife conflicts and restricted access to resources. Similarly, **Robalino *et al.*, (2020)** analyzed community perceptions in Latin America, showing that positive perceptions of protected areas were often linked to economic benefits from tourism and sustainable resource use. On the other hand, studies like **Chung *et al.*, (2021)** highlighted gaps in awareness and negative perceptions stemming from exclusionary conservation policies, which limited access to traditional livelihoods and exacerbated socio-economic inequalities.

Furthermore, few studies have systematically integrated community perceptions with scientific assessments of ecosystem services**. Castro *et al.* (2022)** called for interdisciplinary approaches that merge ecological modeling with community-based methods to better align conservation objectives with local priorities. Additionally, research on arid and semi-arid regions remains sparse, despite the unique challenges these areas face in balancing ecological sustainability with community needs.

2.8.4.1. Local Knowledge of community about ecosystem services

Indigenous and local knowledge systems play a crucial role in recognizing and managing ecosystem services (Berkes *et al.,* 2000). In many cases, traditional ecological knowledge (TEK) provides valuable insights into sustainable resource use and ecosystem management (Folke *et al.,* 2005). For instance, communities in tropical forests often have detailed knowledge about plant species used for medicinal purposes, which can be integrated into biodiversity conservation strategies (Rocheleau e*t al.,* 1995).

2.8.4.2. Impact of Ecosystem Services on Community Livelihoods

Communities living near protected areas often depend on ecosystem services for their livelihoods, including access to resources like fuelwood, water, and medicinal plants. Studies show that communities value provisioning services such as timber, food, and water, while also emphasizing the cultural significance of cultural services like recreation and spiritual connections to the landscape (MacGregor *et al.,* 2015).

2.8.4.3. Factors Influencing Community Perceptions about ecosystem services

Several factors shape community perceptions of ecosystem services, they are:

1- **Socio-economic status:** Higher-income communities may have less direct reliance on provisioning services but place more value on regulating and cultural services.

2- **Education:** Higher levels of education can correlate with greater awareness of the importance of ecosystem services (Kumagai, 2012).

3- **Resource access:** Communities with limited access to resources may place higher importance on provisioning services (Cinner *et al.*, 2009).

2.9. Methods for Studying Ecosystem Services and Community Perceptions

a- Quantitative Approaches

Quantitative methods for assessing ecosystem services include remote sensing and spatial modeling to estimate service provision across large landscapes (Turner *et al.*, 2007). Economic valuation techniques such as contingent valuation and choice experiments are commonly used to quantify the monetary value of ecosystem services (Bateman *et al*., 2002).

b-Qualitative Approaches

Qualitative methods like interviews, questionnaires and discussions allow for deeper insights into community perceptions and social-cultural aspects of ecosystem service use. These methods are particularly useful in understanding local knowledge and values (Tengö *et al.*, 2014) which we used at this study.

c-Mixed-Methods Approaches

A growing trend in ecosystem services research is the use of mixed-methods approaches, combining both quantitative and qualitative data to capture the full range of ecosystem service values and community perceptions (Kenter *et al*., 2016).

CHAPTER 3. STUDY AREA & METHODOLOGIES

3.1 Study Area

Al Saleel Nature Park Reserve is declared as National Reserve on 28 June1997 by a Royal Decree No. 50/97. It has been designated with the aim of future development for educational purposes, wildlife conservation, and tourism and bringing benefits to local people. It is the largest site in the Middle East, which is considered as a habitat for the Arabian Gazalles. The Nature Park Reserve is located in the Wilayat of Al Kamil W'al Wafi in the Governorate of South Al Sharqiyah at elevation vary from 175 -255 m above sea level, at a distance of about 310 km from Muscat and 57 km from Sur (**Figure.1**). The park covers an area of 220 kilometers square.170km^2 of it is dominated by *Vachellia tortilis* forests.

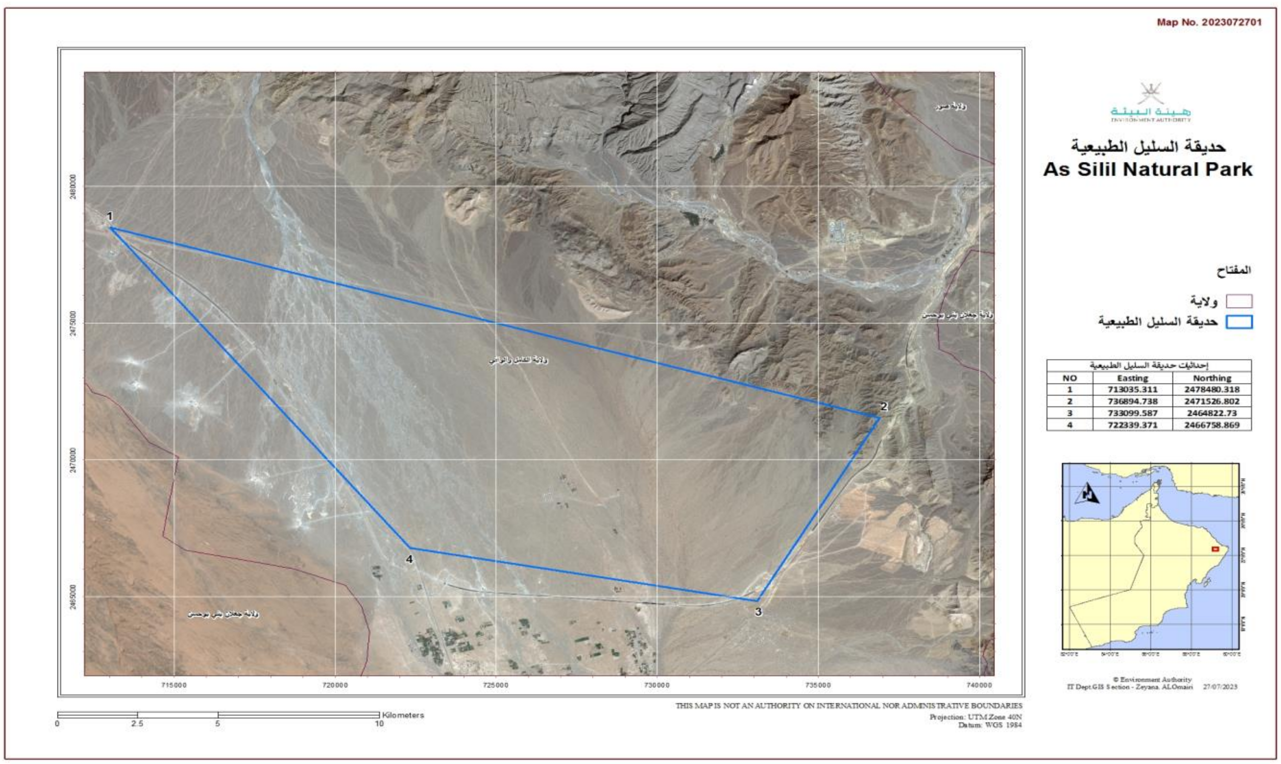


Figure.2. As Saleel Nature Park Reserve (source: EA, GIS department 2023)

The temperature is low during winter (Oct-Mar) while in summer the temperature reaches more than 40ºC. The average annual temperature according to nearest meteorological station in the area is vary between 23.8-30 ℃. (**Figure 2**).

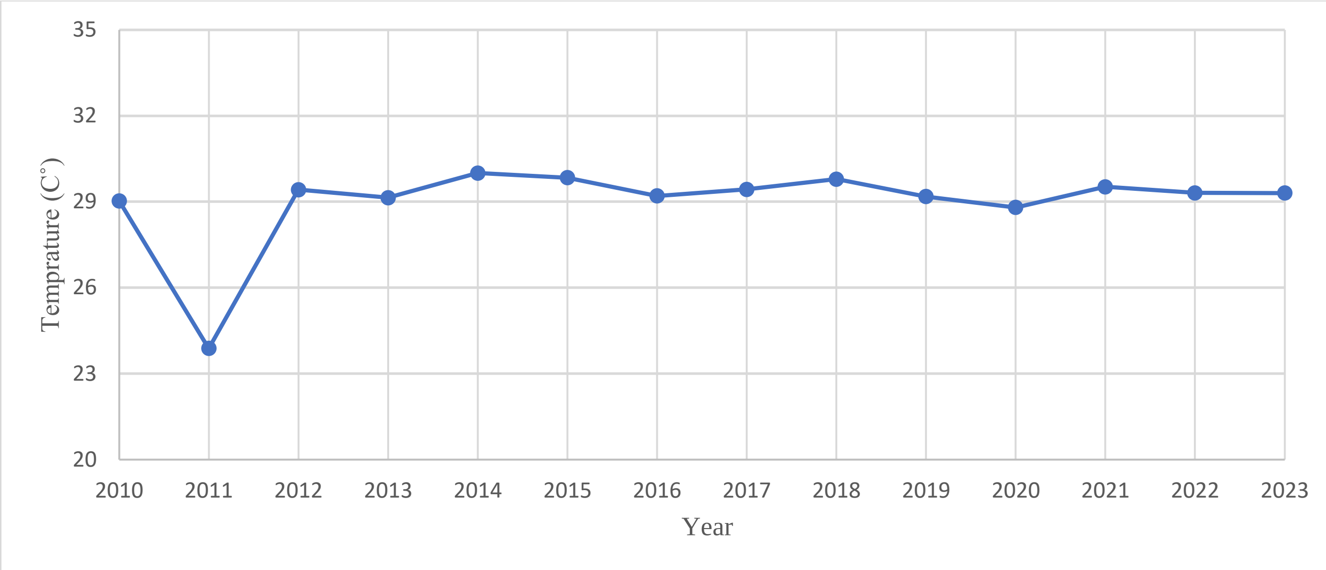


Figure 3.: Show the annual average temperature at study area (Source: CAA, 2025)

It is located in the belt of arid and semi-arid areas where the amount of annual rainfall in some years is low. (**Figure .3**).

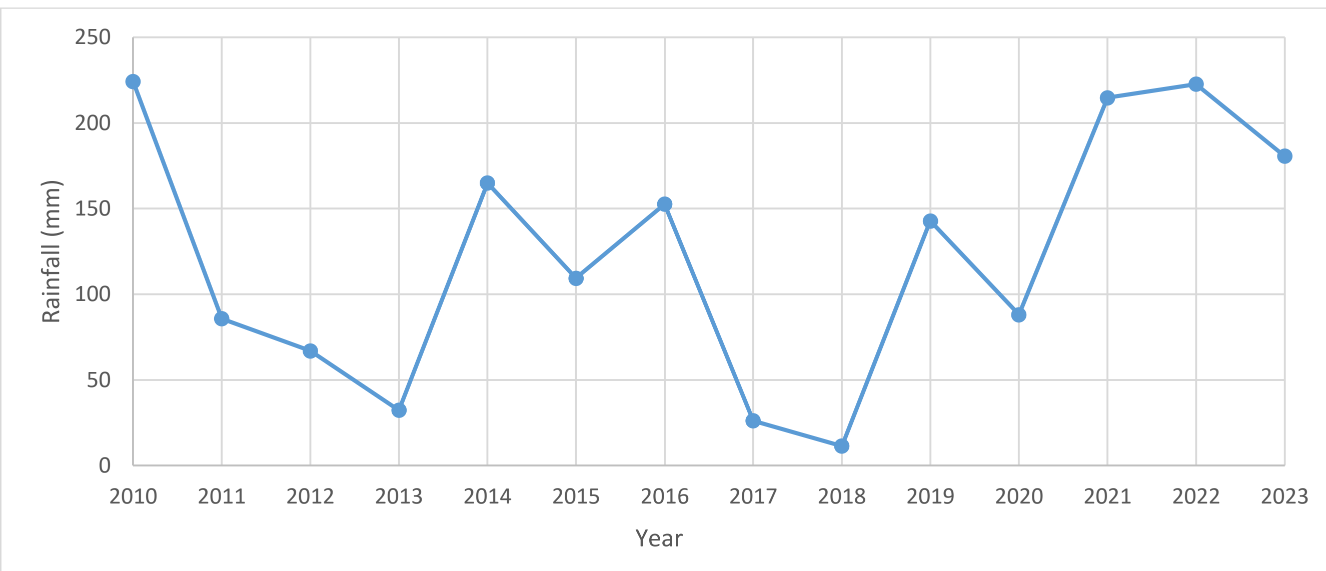


Figure .4. Shows the annual average rainfall (CAA,2025)

Al Saleel Nature Park Reserve (SNPR) is distinguished by a variety of physical and natural components that give the reserve a unique importance. Eastern Al Hajar Mountains Range is located in the north part of the park where there are fossil formations, an indication of the location of the area in shallow waters millions of years ago. The reserve has a unique biological diversity in the environmental unit of the Interior Eastern Plain.

It is characterized by a wide spread of forests of Acacia trees, and more than 100 species of wild plants and trees while there are more than 8 types of mammals, such as Arabian gazelle, Arabian fox, red fox, Omani wild cat, and wild rabbit, as well as other types of small mammals, in addition to more than 30 species of wild birds. As for the reptiles, 8 types of reptiles were seen in the reserve and 166 species of insects. Most predominant vegetation in the study area is *Vachellia tortilis* woodlands, while the most dominant wildlife is the Arabian Gazelles (Protected areas of Oman ,2021, EA)

3.2 Methodologies

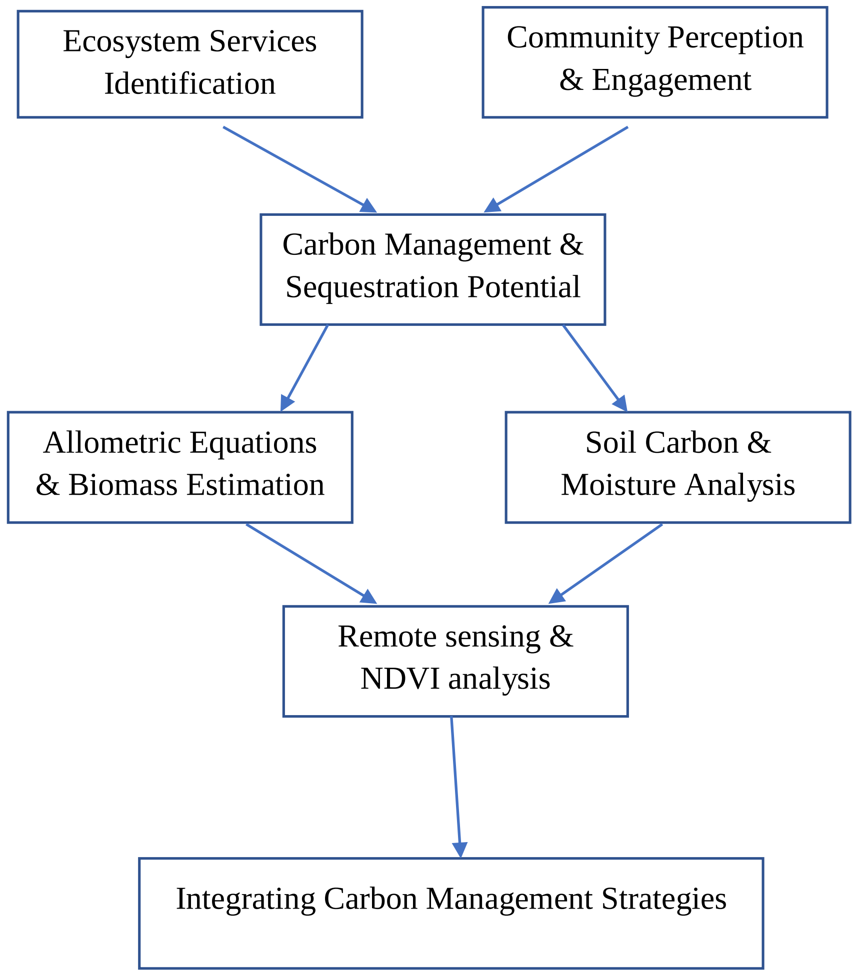


Figure.5. Diagram of Conceptual Framework for Ecosystem Services & Carbon Management

The above diagram illustrates the interlinked components that guide the identification of ecosystem services and carbon management strategies in the study area. It begins with the identification of ecosystem services and community perception and engagement, which provide critical insights into the socio-ecological value of the landscape and the role of local knowledge and participation in environmental management.

These inputs feed into the evaluation of one important ecosystem service which is carbon management and sequestration potential, which serves as the central theme of the research. To quantify this potential, the framework incorporates allometric equations and biomass estimation for aboveground carbon, alongside soil carbon and moisture analysis to account for belowground and soil-based carbon stocks.

Further, remote sensing and NDVI (Normalized Difference Vegetation Index) analysis are employed to spatially assess vegetation health and land cover dynamics. The integration of these biophysical, social, and technological components ultimately informs the development of context-specific carbon management strategies that align with both ecological sustainability and community needs.

This framework ensures a holistic and interdisciplinary approach, linking field data, remote sensing, and stakeholder perspectives to inform practical and scalable solutions for carbon management in arid or semi-arid ecosystems.

3.2.1. Developing Site specific –species alometric equation (Models) to estimate carbon sequestration

Preparation for the field work

Tree harvesting is prohibited by Environmental laws in Oman. So, Prior to start destructive sampling work, We looked for a place where we can do the destructive sampling of *Vachellia tortilis* .Two Options was discussed with the Environment Authority Staff. The first one is to find infrastructure or development projects where Vachellia trees will be cut .The other option is to discuss with EA to do destructive inside the reserve for the research purpose. Finally, we knew that OQ Company (Gas & petrochemicals) got an environmental approval to lay a gas pipeline from Fahud to Sur and the pipeline will crosscut the reserve **for 15 km** long and many Vachellia trees locate on the proposed line will be removed. Then the proposal discussed with the company and EA which they give permission and support to do the work. The proposed gas pipeline located towards the northern part of the reserve near to border **(Figure.6)**

Prior the research work, three site visits during summer period (April -May2021) were done to the area, two of them specifically to the proposed gas pipeline area to see the points where the pipelines will come and to see the density of Vachellia trees along the proposed line. Also, to have an idea about the environment there.

So for the next steps, preparatory work started to be done such as preparing the instruments to be used at the field like GPS, measuring tapes, Camera, colored nails, clinometer, Gloves and plastic cards with papers.

The plastic cards needed to number each tree for the classification and destructive sampling methodology later on.

Figure.6 . Show an overview along 15km distance of the proposed gas pipeline

Vachellia trees were seen healthy and not affected by grazing at this area (**Figure.7)**

Figure .7. *Vachellia tortilis* tree at destructive sampling area

By using GPS (Garmin), Coordinates at different location along the proposed line where taken during the site visit and put them into google earth map. The availability of Vachellia trees along the line were circled at the a google earth map.

One site visit for the whole day was done to draft a design the research experiment for the destructive sampling and to try different variables measurements of the trees.

The field work started with primary data -inventory to have an idea about the trees sample in the area since there was no inventory data before so, it was decided to establish circular plots (12.5m*12.5m) at the left side of the proposed line to be used for field work survey to prepare the destructive sampling at **8** different locations where Vachellia trees are available Because according to the regulation and permission, gas pipelines projects must have 25 m as buffer zone from both sides and left side chosen because an existing gas pipeline there.

The plots were laid in the areas along the line where there are Vachellia *tortilis* trees. Coordinates of each plot were taken using Global Positioning System (GPS). For each tree inside the plot, Dimeter at stump height (DSH), tree height (H) and crown area (CrA) were measured. Since most of the tree at the study area were branches at 0.3 and below, the circumference of each tree was measured at 0.3 m .

A total of 40 trees were measured in all the 8 plots. **(Figure.8.)**

Measuring tape were used to measure Diameter at Stump Height (DSH) and Crown Area (CA) and the tree height (H) were measured using clinometer. It was found that the reserve had different ecosystem /environment. there is wadi, plain and hilly/rocky areas. There were no *Vachellia tortilis* found on the wadi and less tree was found on the hilly and rocky environment .so, 8 plots were made along the proposed gas pipelines, at plain area only.

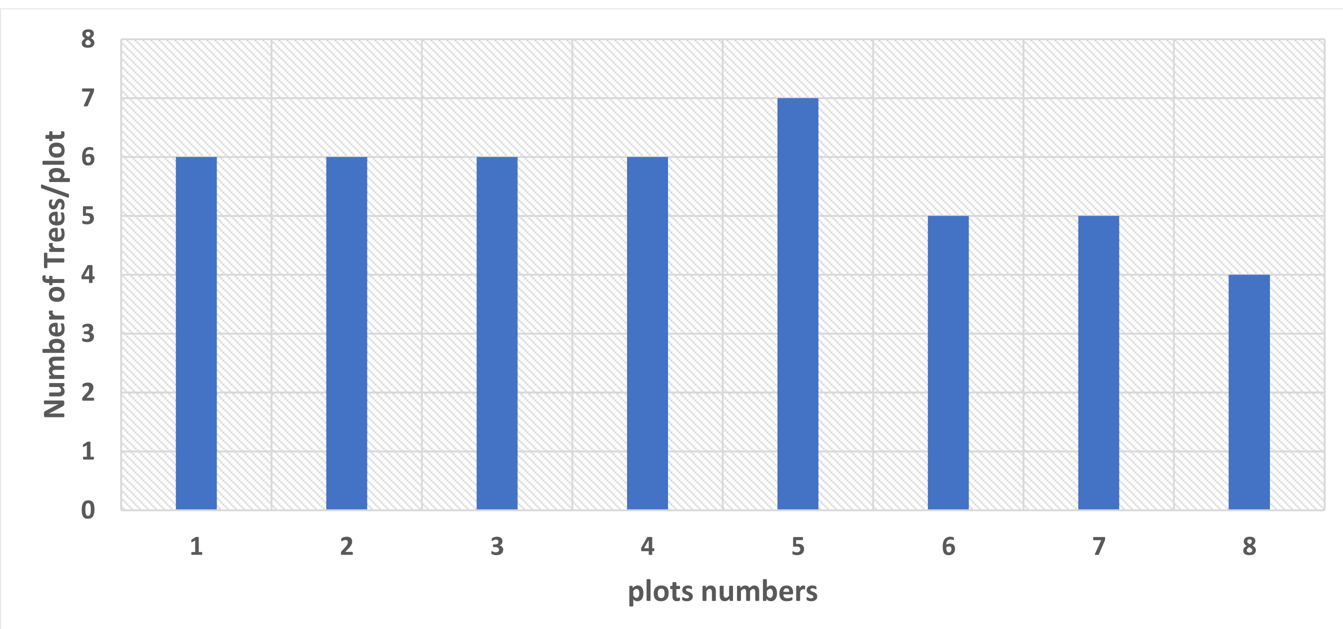


Figure.8. Distribution of *Vachellia tortilis* in all 8 plots

The work done at September 2021 winter time where temperature is low.it was started by located the plots on a google earth map and the coordinates of the center of each plot were written on a datasheet for inventory data collection. Then, the coordinates were put on the GPS for plot 1 to 8. Later, the work started at the field with the help of the reserve staff there to find each plot so we started by plot number 1 .The proposed gas pipeline sign was found and by using the measuring tape 12.5 meters were measured from the proposed pipeline towards the north to locate the center of the plot .Then a 12.5 meter measured to complete the hole plot and a dead stick was put to show the border of the plot. Then the measurement of the trees inside the plot were done started from the north towards clockwise. the DSH was measured above 30 cm by using measuring tape (**Figure .9).**

Figure 9. Measurements of Diameter at Stump Height (DSH) in destructive sampling area

Then two persons measured the crown area (CA) of each tree and that was done by one person standing at northern side (point A) where another one stands at southern side of the tree (point B) by using measuring tape also **(Figure.10)**

Figure .10. Measurements of Crown Area (CrA)

Finally, the height of each tree was measured by using the clinometer.

Plastic cards with numbers were put on each tree started at number 1 for the first tree measured at the plot for the classification and destructive sampling later on **(Figure.11)**

Same methodology was applied for the remaining 7^{th} plots at line.

Figure.11. Placing Plastic Card with identification numbers on the tree

The DSH measurements were classified into classes: young size including dimeter of tree below 40 cm , pole -size include dimeter range from 41-63 cm and the standard size include dimeter measurement above 63 cm. (**Figure.12)**

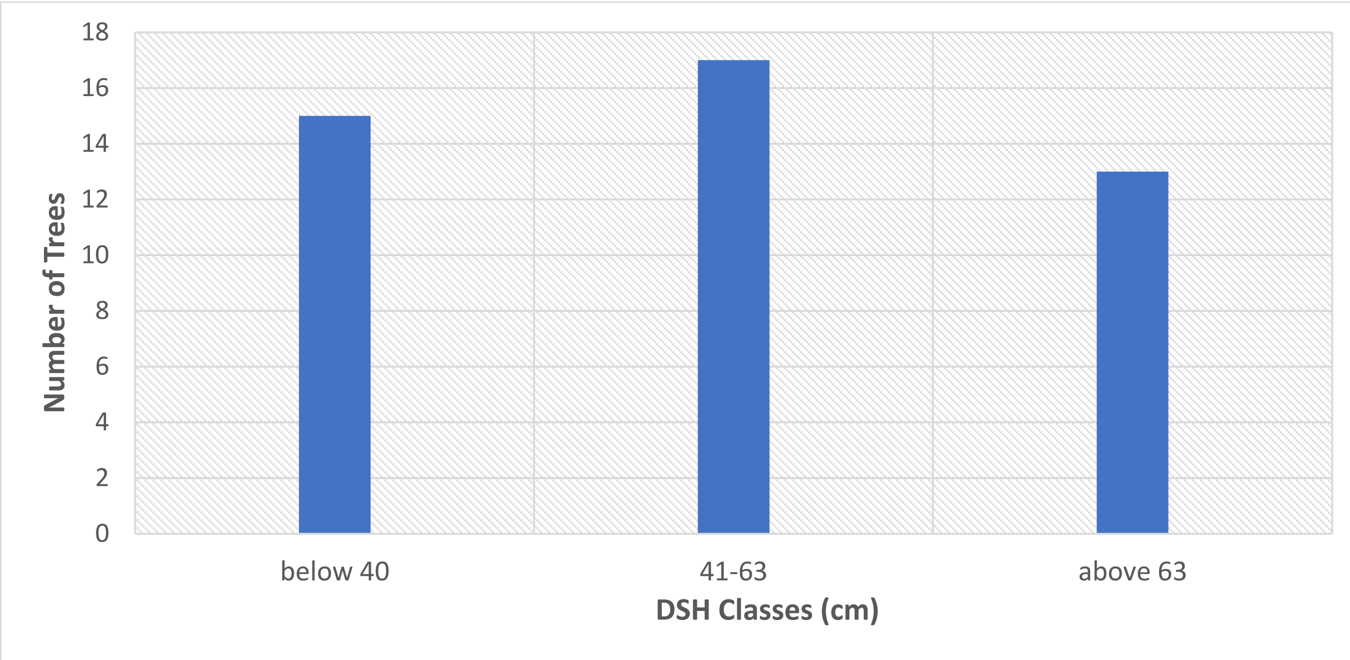


Figure.12. DSH Classes distribution among *Vachellia tortilis* in the destructive sampling area

Before we started the destructive sampling, site visit done to the field to have an idea about the area , the way of collecting samples, , and where to put them and the the weighing process also .Moreover , it was also important to know the period of time we put our sample inside oven for drying. Not only that but to find any issue or challenges during running your experiment in order to avoid them later. And since the study area is very far from the university labs, the idea was to decide these issues before going to the field.

So was decided to go to the botanic garden at college of science in university to look for any *Vachellia tortilis* and get some small parts from it. So after approval from botanic garden staff, we went there .

Different DSH and height size-class were selected to take samples from and by using cutter we started to cut small parts of branches, twigs and leaves but was not possible to cut the big stems.

The samples were collected in plastic tray, and leaves and twigs parts were put into tissue to avoid drying or losing their parts.

At the lab, different samples from different parts of two *Vachellia tortilis* trees were prepared and cut into small parts suitable to put into the oven.

The fresh weight for each part of the samples were taking using two electronic balance for accuracy and the value put into collecting data sheet prepared for the same purpose in the field.

first the oven temperature was fixed at 70 C˚ for twigs and leaves and 90 C˚ for branches and the weights were taken every day to monitor the change in order to know if still there is any moisture or not .so we took weight after 24 hours and after 48 hours. we got the results

Before destructive sampling work started, the inventory data were used for selecting the tress to be harvested from each plot in the areas

The selection process was done based on the outcomes from the regression between the variables (DSH, H, so to make sure that we choose variety of trees among different DSH and H **(Figure.13.)**

The represented 20 *Vachellia tortilis* trees were selected based on DSH and H. The 20 trees were among different classes.

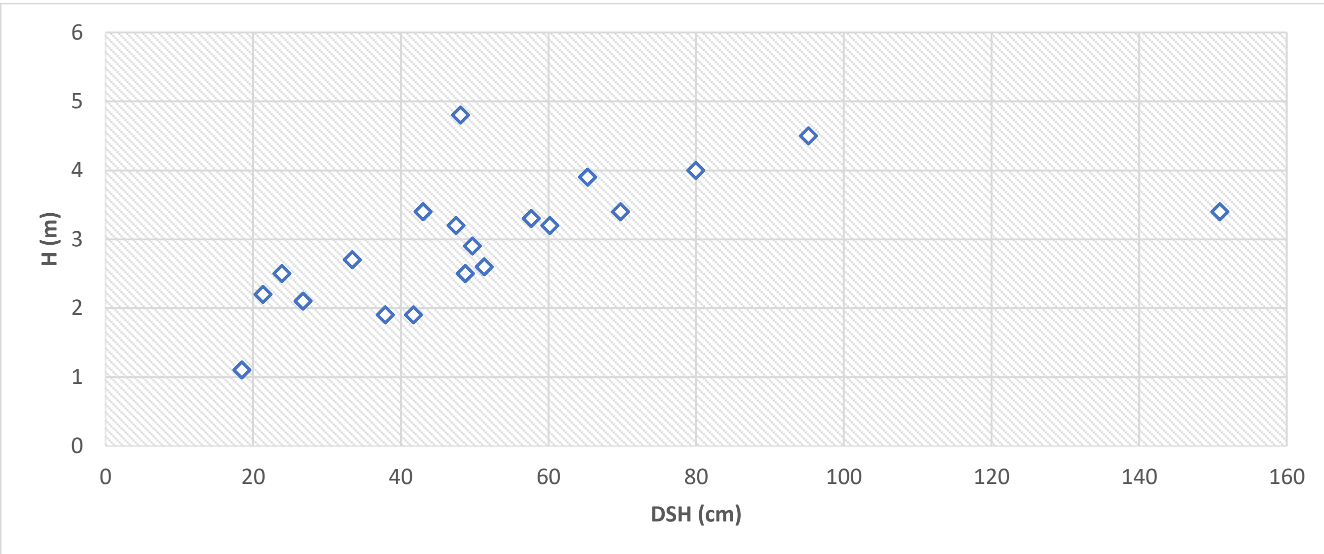


Figure.13. Relationship between DSH & H of the harvested *Vachellia tortilis*

Approvals were obtained from Environment Authority for starting the work and from As Saleel Nature park reserve department for the entrance of the company to do the destructive sampling within the affected area by the project inside the reserve. The guideline prepared for the destructive sampling were send to the company before months.

Prior to the work, meeting at the field were held to discuss the guidelines again with workers to make sure they understood each step and if any questions related to the work can be answered by the researcher.

The work team included: excavation machine driver, two workers, four-wheel car driver, two people for HSE check during the work.

We preparedplastic bags, plastic containers, 300 kg spring balance, , two electronic balances, ropes, GPS , permanent markers and stapler .

The methodology for the tree removal and subsamples collection process for the destructive sampling is as the following: **(Figure 14.)** (Eshete and Ståhl , 1997) ,(FAO ,2001 and 2009) , (Bagnall-Oakley, S. A., *et al.* 2019), (Farsi, M., *et al.* 2014) , (Sebrala *et al* .,2022) , (Roxburgh *et al*.,2006) , Picard *et al* ., 2012)

Three workers began the process by carefully removing the soil surrounding the roots of the marked trees. This step was performed to prepare the trees for excavation, ensuring that the root systems were exposed and ready for extraction.

The marked trees were extracted using an excavation machine, with the assistance of the workers. The trees were carefully uprooted by cutting the base of the tree and lifting it out of the soil to minimize damage to the root system.

Once extracted, each tree was weighed in its entirety using the excavation machine, rope, and a spring balance. The tree was suspended by the rope, and the weight was recorded accurately. If needed, the tree was divided into sections, with each part weighed separately.

Small samples, approximately 250 -300 grams in weight, were cut from each part (stems, branches, twigs, and leaves) using a hand saw. These samples were then weighed using an electronic balance

The collected subsamples were transferred into plastic bags or plastic containers to ensure they were preserved properly for laboratory analysis. These samples were carefully transported to the laboratory at the University for further work.

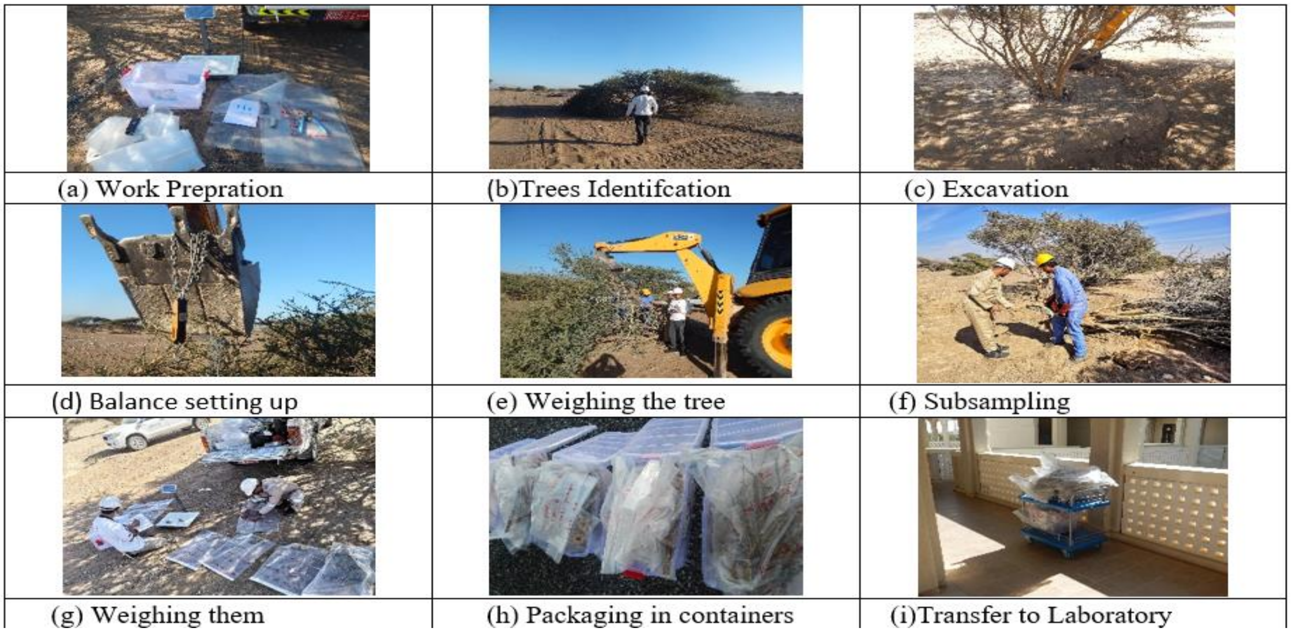


Figure.14. Destructive Sampling Steps

Drying oven and electrical balance was needed to this work in the laboratory. The collected sub-samples from the field were brought to dry at the oven at different temperatures as the following:

105 C (Stems), 85 C˚ (Branches) and 75 C˚ (Twigs & leaves) for 3 days. All sub-samples were weighted every day at the electronic balance and the data were recorded. This process was repeated until we reached a constant weight (**Figure.15.) (**Bayen *et al* ., 2020) **(** Abebe *et al* ., 2024 **)**

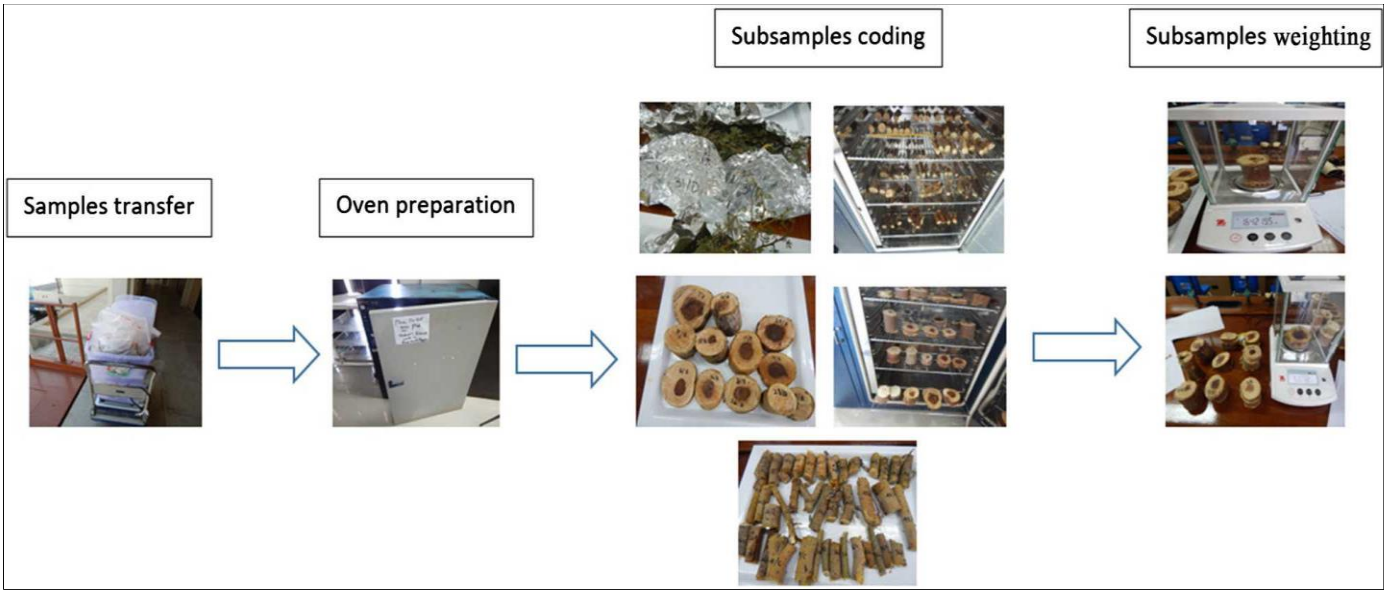


Figure.15. Subsamples Preparation and lab processing for weight determination

3.2.2. Quantification of carbon sequestration potential of *Vachellia tortilis* using field measurement & existing allometeric equation.

3.2.2.1. Preparation of field work

Two primary site visits are needed to the area to identify possible sampling technique and measurements and this helped in preparing proper sampling techniques. The plain area which is about $170km^2$ is purposely chosen for sampling for carbon sequestration but because of reserve is open more grazing at some parts of the area and also there were human activities there. Moreover, some trees are died there also.

Also because of limited of time and resources, approximately 0.980 km2 were chosen as sampling area.

3.2.2.2. Sampling design

The topography of the reserve is varying between rocky, wadi and plain areas. As it was mention above, the dominant plant species in the area is *Vachellia tortilis* .Based on satellite imagery of the area (the pleadris ,2021 March) a part of the plain area at the middle was chosen for this objective based on site visits and

the classification done by ENVI 5.0. The area was almost rectangle in shape where forest of Acacia species is distributed on it. It is located in the middle of the reserve. The coordinates of this sub-study area were located on google earth first and then by using GPS in the field.

According to different site visits to the area and to satellite images , the elevation in the study area is vary between 175 -208 m .so based on that the researcher would like to study the impact of elevation on carbon stock value in the area so stratification sampling was applied .The area is divided into two main sub-area (low and high elevation) and a scale has been developed by the researcher to differentiate between low and high elevation.0-190 m is set as low elevation whereas from 190 m and above treated as high elevation.

Circular 30 plots (17m*17m) distributed in 3 transects lines were laid starting from low south to north of the study area.100 m distance set to be between each transect lines and the other and between centers of each plot (**Figure.16.).**

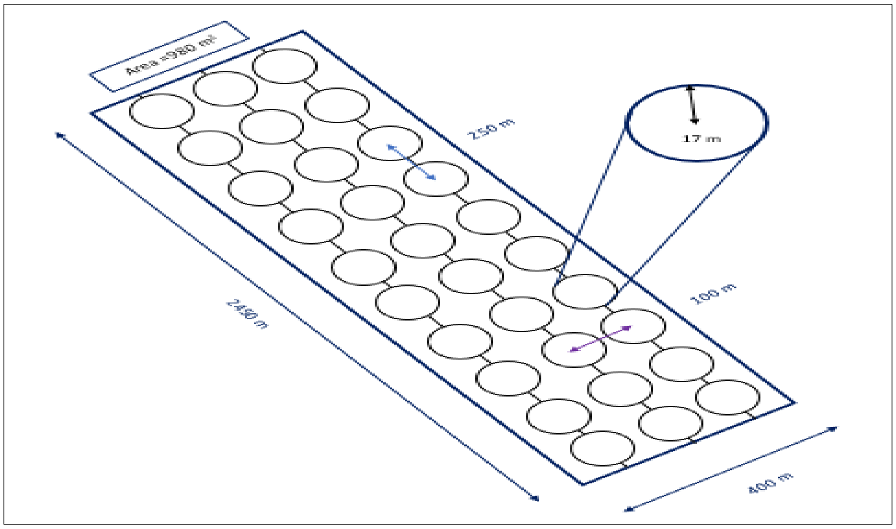


Figure.16. Sampling Design for biomass estimation in the study area

3.2.2.3.Aboveground Biomass (AGB) & Below Ground Biomass (BGB) Calculations

Aboveground biomass refers to the total mass of living vegetation (leaves, stems, branches) present above the ground. It is a key indicator of forest productivity and plays a significant role in carbon sequestration. AGB was estimated using an existing following formula:

ln(TDW)=−3.514+2.827ln(DSH)\ln(TDW) = -3.514 + 2.827 \ln(DSH)ln(TDW)=−3.514+2.827ln(DSH)

Where:

- TDW is the total dry weight of the tree (kg).
- DSH represents the diameter at breast height (DBH) in centimeters.
  This formula, sourced from Giday *et al*. (2013), is a regression-based model that relates the tree's diameter at breast height to the total aboveground biomass, accounting for tree species and local environmental conditions.

Belowground biomass refers to the mass of roots and other subterranean parts of the tree. It is crucial in understanding the total carbon storage of an ecosystem, as roots play an essential role in nutrient cycling and carbon sequestration.

Belowground biomass was estimated by using a common conversion factor based on the aboveground biomass (AGB):

$$BGB = AGB \times 0.2$$

Here, AGB is the aboveground biomass (kg), and the multiplier 0.20 represents an approximation commonly used in forest biomass studies, particularly in arid and semi-arid regions (Source: Siraj, 2019). This implies that for each kilogram of aboveground biomass, approximately 20% of that weight is found in the roots.

The biomass stored in both the aboveground and belowground parts of the tree is primarily composed of carbon. To estimate the carbon stock in the biomass, a general conversion factor is used:

$$\text{Carbon Stock} = \text{Biomass} \times 0.5$$

The factor of 0.5 is based on the assumption that approximately half of the biomass is carbon by weight (Source: Siraj, 2019). This conversion is crucial for estimating the carbon storage capacity of a forest or ecosystem, as carbon sequestration is a key indicator of climate mitigation potential.

Once the carbon stock was estimated then it was converted to CO_2 equivalent (CO_2e) to understand the impact in terms of climate change mitigation. This conversion accounts for the fact that carbon dioxide (CO_2) is the main greenhouse gas associated with climate change, and its equivalent is used to estimate the global warming potential.

since:

- The molecular weight of carbon (C) is **12 g/mol**.
- The molecular weight of CO_2 is **44 g/mol**.
- $44/12 = 3.67$

The formula simplifies to:

$$CO_2 \text{ equivalent } (CO_2e) = C \times 3.67$$

Where:

- C is the carbon stock in kilograms.
- 44/12 the molecular weight ratio of CO_2 to carbon (44 for CO_2 and 12 for carbon).
- The factor 3.67 is used to convert the mass of carbon to the equivalent mass of CO_2.

Three hundred and fourteen (314) trees were measured in 30 plots in the study area. DSH Variable was measured using measuring tape. The distribution of *Vachellia tortilis* measured in the study area is shown in **Figure.17** below:

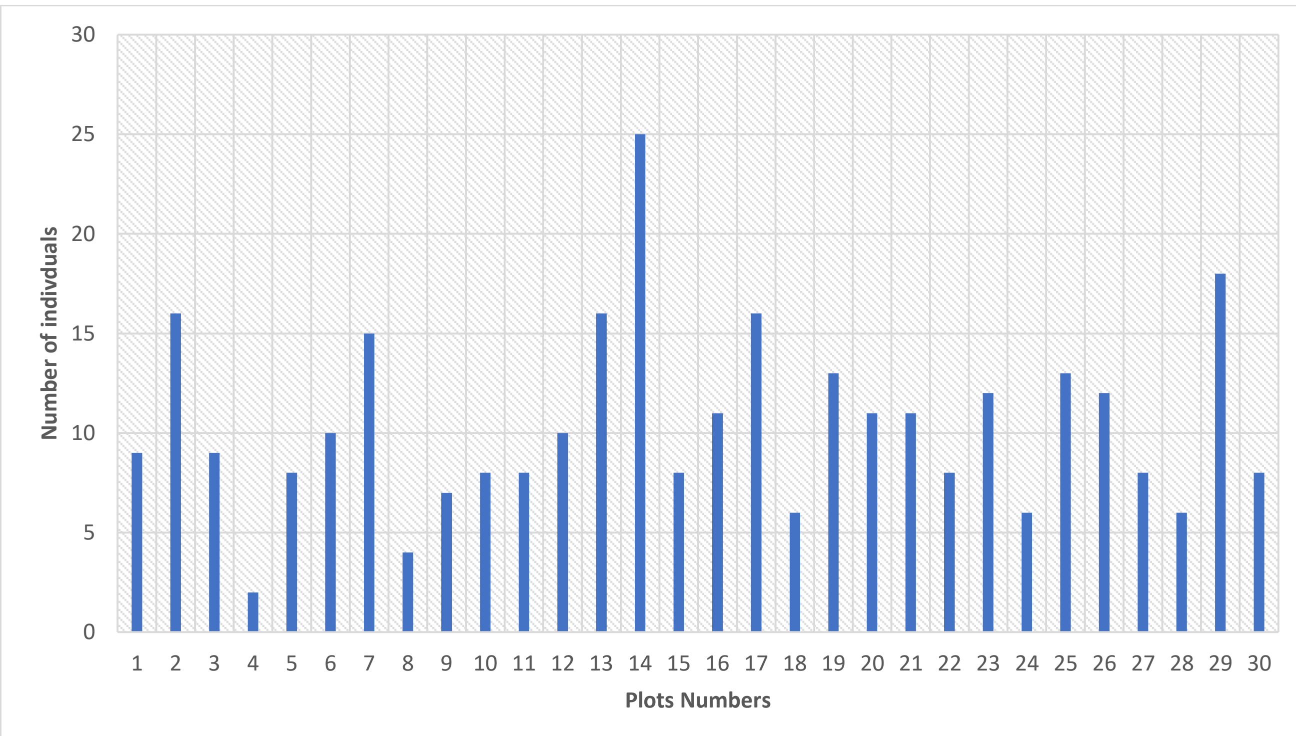


Figure.17. *Vachellia tortilis* distribution in the 30 plots study area

Global position system (GPS) were used to locate the center of each plots

Dimeter at sump height measured at 30 cm .and it is included because most trees at the ares have multi stemming beyond 30 cm from ground surfaces. these plots were laid on google map with coordinates and GPS used to locate them in the field by the help of the reserve staffs (**Figure.18.)**

Figure.18. GPS positioning of the plot in the study area

The DSH (Diameter of Stem Height) of tress within each plot measured using measuring tape and tree will be marked by marker tape once finish the measurement. (**Figure.19)**

Figure.19. DSH Measurements for biomass determination

All *Vachellia tortilis* was classified based on DSH classification into 5 DSH classes (0-20 cm,20-40 cm, 40-60 cm ,60-80 cm and above 80 cm) .Majority of *Vachellia trotilis* in the study area falls in 2nd DSH class (20-40 cm) , **(Figure.20.)**

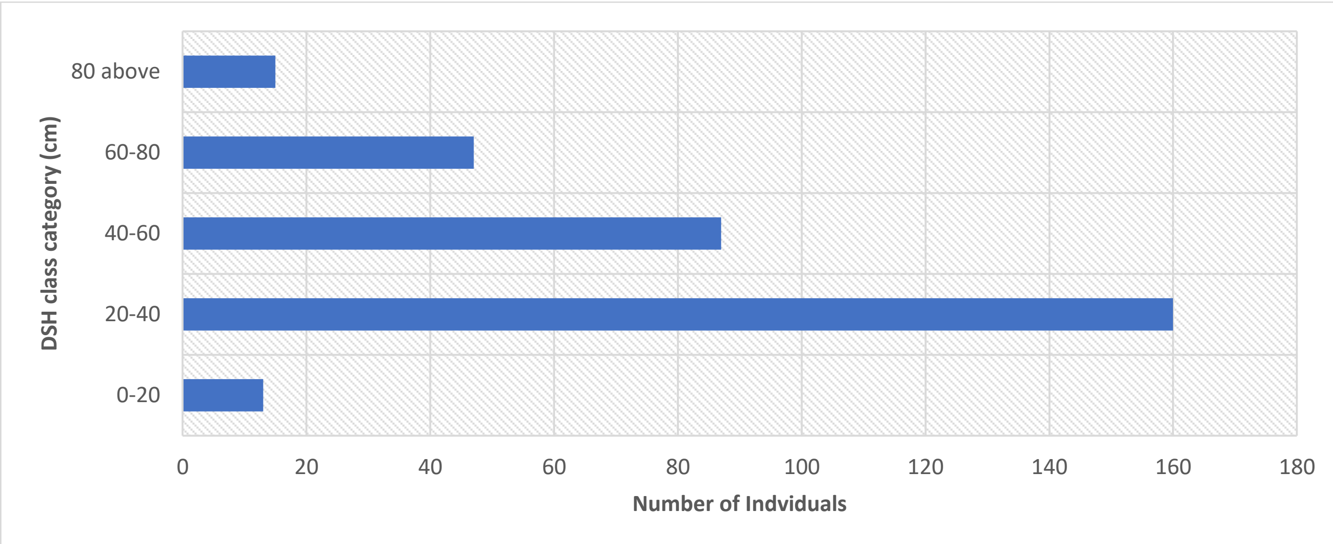


Figure.20. DSH –Classes Distributions of *Vachellia tortilis* in the study area

3.2.3. Soil Organic Carbon and soil moisture determination

3.2.3.1. Soil Organic Carbon determination

Soil Organic Carbon (SOC) is an essential component of soil, influencing soil fertility, structure, and microbial activity. The Walkley-Black method is widely used to determine SOC in soils because it is relatively simple and quick. Soil samples collected from the 30 plots in study area using a composite sampling method.The 30 composite samples were collected from the 0-15 cm soil depth using soil aguar, ensuring that the samples are representative of the entire area **(Figure.21.)**

Figure.21. Soil Samples Collection for carbon and moisture determination

The Samples were collected from the center of each plot and from 4 points within the plot (north, south, east and west). Samples were collected in airtight plastic bags with a written identification of plot number and date of collection **(Figure.22)**

Figure.22. Soil Samples Collected in Plastic Bags for laboratory analysis

Samples were air-dried and sieved through a 2-mm mesh to remove debris and large particles.1gm of air-dried -sieved soil was weighted into a 250 mL conical flask and then 10 ml of 0.4 N potassium dichromate solution was added to the flask. The solution was Swirled gently to mix the soil and reagent. 20 mL of concentrated sulfuric acid added drop by drop while swirling continuously to avoid spillage. The flask was allowed to sit for about 30 minutes, giving time for oxidation of organic matter. After the oxidation reaction, 200 mL of distilled water was added. The excess potassium dichromate Titrated with a 0.5 N ferrous sulfate ($FeSO_4$) solution using the indicator. The titration proceeded until the color changes from red to green, indicating the end point. The volume of the titrant used for each sample was recorded **(Figure.23.)**

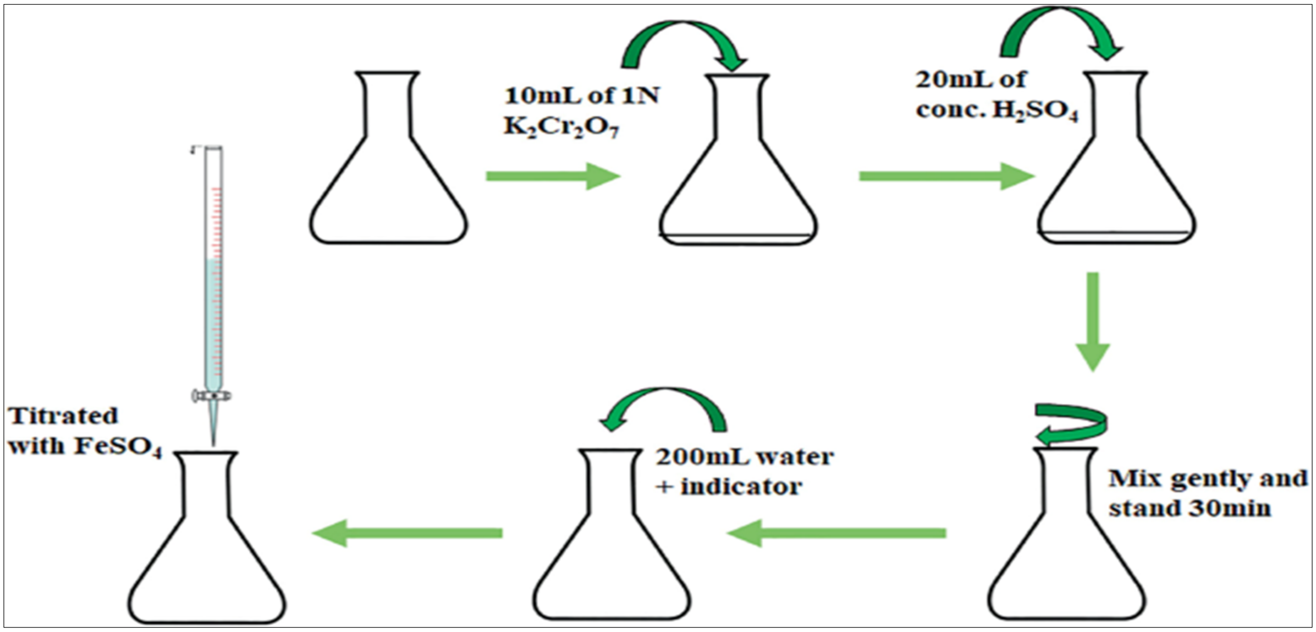


Figure.23. Titration Procedures for SOC% determination (Source: FAO Manual Guideline,2019)

The amount of SOC is determined by comparing the amount of potassium dichromate that was reduced by the organic matter in the soil with a standard calibration curve. The formula to calculate SOC is:

$$(SOC\%) = \frac{(V1 - V2) \times N \times 0.003 \times 100}{W} \quad ; \quad \text{(FAO Manual Guideline, 2019)}$$

Where:

- V1 = Volume of potassium dichromate before reaction (mL).
- V2 = Volume of titrant used (mL).
- N= Normality of potassium dichromate.
- W = Weight of soil sample (g).

The factor 0.003 accounts for the molecular weight of organic carbon.

3.2.3.2. Soil moisture determination using composite soil samples

Soil moisture is a vital factor in soil science, affecting plant development, soil structure, and nutrient cycling. Assessing soil moisture yields information regarding soil water retention, availability, and evapotranspiration dynamics.

Composite soil Samples collected for soil organic carbon assessment from a depth of 0-15 cm consisted of 30 composite samples from 30 plots over 3 transects to account for heterogeneity. The fresh weight of all 30 soil samples was recorded. A specified mass of the fresh soil sample (about 50-100 g) was placed in the container. The weight of the sample was recorded in data sheet (W_1). Soil samples were desiccated in an oven at 105°C for 24 to 48 hours or until a consistent weight was achieved. (Kisiksi , 2011).

The samples were reweighed post-drying (W_2). The soil moisture content (%) is determined using the formula:

$$\text{Moisture Content (\%)} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times 100 \quad \text{(Source: ASTM, 2010)}$$

Where:

Wet Weight (W_1) = Weight of the soil sample before drying.

Dry Weight (W_2) = Weight of the soil sample after drying in an oven at 105°C until it reaches a constant weight.

3.2.4. Evaluation the effectiveness of NDVI and remote sensing techniques in monitoring vegetation health

Two 50 cm resolutions satellite image were ordered in cooperation with remote sensing and GIS centre at Sultan Qaboos University from Geocento company was captured by the Pleiades Satellite on 6th February ,2021. The remote sensing part at the research was started in 2021. (**Table.1)**

Table 1. The specification of the two satellite images

Product	Date	Ground sampling distance (nadir)	Coverage
The Pleiades	6/2/2021 6:48	50 cm	63.9 km2
The Pleiades	6/2/2021 6:46	50 cm	113.9 km2

The image of the As Saleel Nature Park Reserve became two parts, the first one covers 63.9 km2 of our study area and the other one covers 113.9 km2.

For the analysis of the satellites images the ENVI 5.0 software were used. It is licensed by center of remote sensing and GIS at Sultan Qaboos University. This software was used because it is available at RS&GIS center at Sultan Qaboos University Also, it is a popular software and one of remote sensing tool in environmental researches. It has been widely used.

3.2.4.1. Preparation of the satellite images

Using ENVI 5.0 software, we started to prepare the satellite image for further analysis by doing mosaicking. Mosaicking is a technique to combine multiple images to get one full image. It is used when your geographical study area is too large and you want more coverage of it.

So first of all, we open the software and we went to open image file button so the images displayed. Then, we went to basic tool button, then Mosaicking. The georeferenced mosaicking was chosen to mosaicked our images. (**Figure 24**). then the location where the image will be saved was selected. The bands for displaying the satellite image were band 3= RED, band 2=GREEN, band 1=BLUE. (Jensen ,2007) .

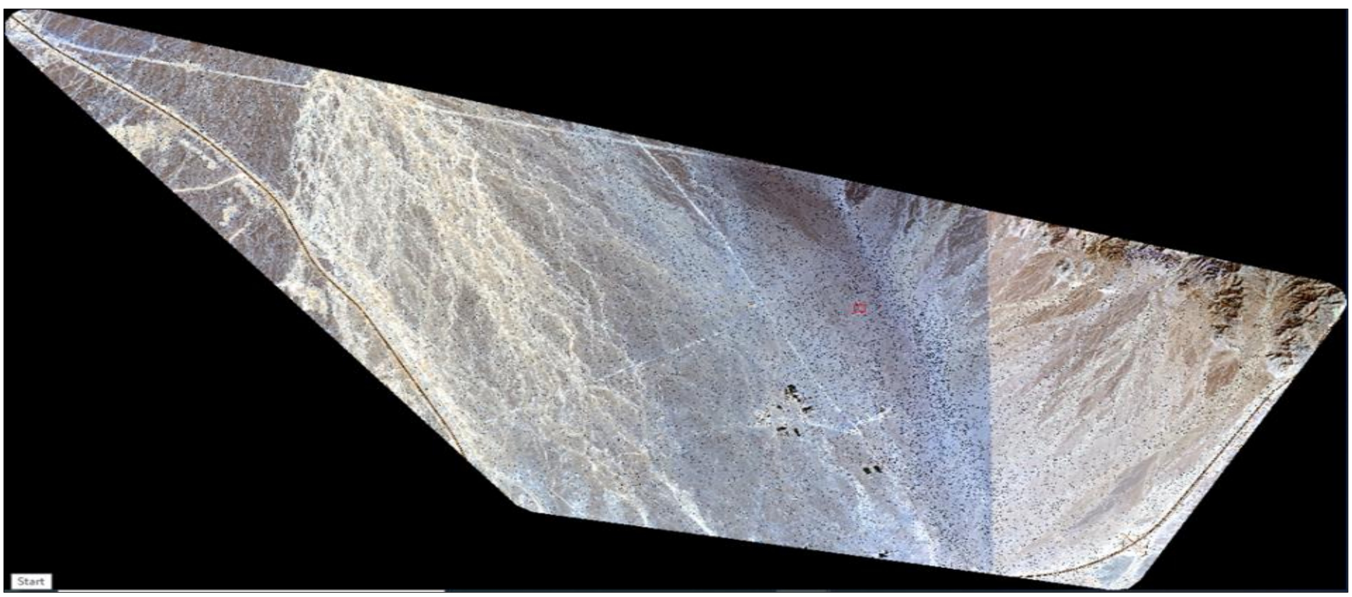


Figure 24. The final satellite image after mosaicking for further analysis

3.2.4.2. Classification of the study area

Before doing classification of the study area using remote sensing technique, Envi 5.0 software, the study area was visited twice to know the topography and the features there .so according to the entrance license I get from environment authority I went there after contacting the head of as Saleel Park department there and his staff to facilitate the site visit. Meeting were held with staff to get an idea and information about the Park. Since it is prohibited to use your own car, the conservation staff at the park were took me in journey inside the park. Many notes were recorded for the further work at the field and there at they are: the distribution of vegetation, the wadi flow, the accessibility of data collection, type of soil and so on.

Then, at the software, we started with supervised classification. This type of classification as mention at literature is always run by giving the information by user to software by selecting small parts from the whole study areas. Envi software 5.0 has many classification methods, they are: Parallelepiped, Minimum Distance, Mahalanobis Distance, Maximum Likelihood, Spectral Angle Mapper, Binary Encoding, and Neural Net.

Maximum likelihood was used to run the supervised classification. Before applying the steps of supervised classification, the Region Of Interest (ROI) were established .This was done by following the steps below:

1- In the box of the original image (display 1 screen), button overly was selected.
2- ROI tools box appeared and zoom image was selected to work with.
3- Some represented parts of study area (eg.vegetation,soil,roads, mountains) were chosen by clicking on the zoom image and making polygons
4- The area and its details chosen appeared at the ROI tool box , the color and ROI name can be changed.
5- ROI were selected to be classify at the study area, they are : Vegetation, asphalt roads ,building , soil and Wadies .
6- New region button was selected to add the new region and change the color of the component, the button color selected, the color at ROI tool box were in gradient (eg. green3 green2, green1..etc)

(Richards *et al* ., 2006).

Then supervised classification was done by following below steps

1- From the toolbar of the software, classification button was selected.
2- Then Maximum likelihood button was selected.
3- The classification input file box was appeared, ROI file was selected
4- Maximum likelihood box parameters appeared and the classes put before were all selected
5- The output button within the box were choose to save the output image file.
6- By clicking OK, the image was saved and directly it opened on the main box where the original image was.
7- Then by clicking on image (saved in new name), Gray color button choose to display the image
8- By clicking on new display, another display appeared with the classification image.

(Congalton & Green , 2009).

After getting the final classification image, many classification colors were appeared and some colors were closed to each other.so, in order to select clear color and easy to define, button overly were selected, and the classification, an interactive class tool box is appeared. All classes and their selected color were appeared.

For a purpose of choosing other colors for the classes, at class tool box the buttons option and the edit class were selected.

Linkage had been done to link the original image and the classification image by clicking on the overlay button.

So, the supervised classification run by trying different number of classes started with 3 classes and then with 7 classes and later, 10 classes was tried. the results were not clear and it gave two color for both the *Vachellia tortilis* trees and the main road there.

Several class ranges were chosen in several time but the results were the same .so the unsupervised classification decided to be done to see how the results will be. 5 Classes were determined (*Vachellia tortilis* , low ground , high ground, small wadies & Gravels)

3.2.4.3. NDVI Calculations

NDVI was calculated to determine the environmental health status of *Vachellia tortilis*.

(Knauer *et al* ., 2014), (Brandet *et al* .,2014) , (Brandet *et al* ., 2017)

The NDVI was calculated using the following formula :

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

Where:

- NIR is the Near-Infrared band value.
- RED is the Red band value.

This index ranges from -1 to +1:

- Values close to +1: Indicate dense, healthy vegetation.
- Values close to 0: Indicate barren or non-vegetated land.
- Negative values: Indicate water or snow.

3.2.5. Identification of key ecosystem services and community awareness & preferences assessment using questionnaire and statistical models analysis

A Survey was conducted over a three-month period from July to September 2022. The objective of this survey is to identify the ecosystem services provided by the nature reserve and assess their significance to the local community. The target population included individuals living in various proximity to the reserve, specifically inside the reserve, those residing within 1 km, 3 km, and 10 km of the reserve, as well as individuals living more than 10 km away.

By evaluating community perceptions and awareness, the survey aims to gather insights that can inform suggestions for improving the reserve’s management and outreach efforts.

The Questionnaire is divided into three parts:

Part 1: General Information

This section collects demographic data, including gender, age, household income, and proximity to the reserve. This information helps to contextualize the responses and understand how different community segments relate to the reserve.

Part 2: Awareness and Knowledge

In this part, respondents share their awareness and understanding of the protected area. Questions are designed to gauge how well the community knows about the reserve and the term protected areas and also about the ecosystem services offered by the reserve and the importance of conservation efforts.

Part 3: Preferences for Ecosystem Services

The final section of the survey focuses on the community’s preferences regarding various ecosystem services. Respondents are asked to indicate which services they value most and how they perceive these services contributing to their quality of life.

The insights gathered from this survey will be instrumental in enhancing the management of the reserve and fostering greater community engagement with its natural resources.

To ensure a comprehensive understanding of community perspectives, a multi-face approach was employed for data collection. The primary method involved face-to-face interviews, which allowed for direct engagement with respondents and facilitated in-depth discussions about their perceptions of the reserve allowing to see if the survey question is understandable by the community and it was a chance to modify, delete and add new questions also. Additionally, the survey team included staff members from the reserve who provided insights and assisted in reaching out to local residents.

To further broaden the reach of the survey, an online link as google form was created, enabling individuals who were unable to participate in face-to-face interviews to contribute their views. This online approach was particularly beneficial for engaging younger demographics, including school students. The survey was distributed to local schools, encouraging student participation and fostering awareness of the reserve's ecological importance among the youth as well as they were as they acted as a focal point to their families in the areas around the reserves.

Overall, this methodology aimed to capture a diverse range of perspectives, ensuring that the findings reflected the views of the broader community surrounding the national park reserve.

3.2.6. Statistical Analysis

To establish the model, we conducted an initial investigation using linear regression to evaluate the relationships between the measured biomass and the predictor variables (DSH, CA, H), assessing their correlations with each other and with biomass. Based on these correlations, DSH and CA were selected as the primary variables for analysis. Consequently, all further analyses were focused on DSH and CA.

Multiple regression analyses were then performed to evaluate the relationship between observed biomass and the predictor variables, generating regression statistics for each model. Variance analysis and P-values were checked to assess model significance.

The best-fitting allometric models for estimating aboveground biomass (AGB) were selected based on the highest Coefficient of Determination (R^2), lowest Mean Square Error (MSE), and significant P-values.

Each models, A, B, C, D was subjected to multiple regression analysis to determine the best-fitting allometric models for estimating biomass. Model performance was evaluated using three key statistical tests:

R^2 (Coefficient of Determination): Measures the proportion of variability in the biomass that can be explained by the model. A higher R^2 indicates a better model fit.

MSE (Mean Squared Error): Quantifies the average squared difference between observed and predicted biomass values.

A lower MSE suggests better predictive accuracy.

P-value: Assesses the statistical significance of the model coefficients.

A p-value less than 0.05 indicates that the relationships observed are statistically significant.

3.2.6.1. Correlation, factor and structural model analysis

Correlation analysis used to identify the relationship between two ESs and Factor analysis applied to assessing ecosystem services (ESs) and how they well or weak explained by the factor.

Structural equation modeling has been used to examine dependencies among the selected ecosystem services

To explore the relationships among ecosystem services, Structural Equation Modeling (SEM) was employed as an analytical tool. The methodology consisted of the following steps:

1. **Data Collection**:
   The survey responses were collected through a structured survey designed to capture community perceptions of ecosystem services in the study area.
2. **Preprocessing and Preliminary Analysis**:
   The data were initially preprocessed by examining the relationships among ecosystem services using a correlation matrix. To determine the statistical significance of these relationships, Pearson's correlation test was applied at a 5% significance level.
3. **Factor Analysis**:
   Following correlation analysis, Exploratory Factor Analysis (EFA) was conducted to identify latent constructs underlying the observed variables. This step ensured that only well-loading variables were retained for inclusion in the SEM model, thereby improving model fit and interpretability.

4. **Structural Equation Modeling**:

SEM was performed using the **R** programming language, specifically employing the `lavaan` and `semPlot` packages. The `lavaan` package was used to specify and estimate the measurement and structure

(Felipe-Lucia *et al.*, 2015).

CHAPTER.4. RESULTS & DISCUSSIONS

This section presents the findings of the study, addressing the key objectives of identification & assessment of ecosystem services in the reserve and community perceptions towards them, developing site-specific allometric equations, estimating carbon sequestration, estimation of soil moisture, and mapping environmental changes using remote sensing technique and NDVI calculations.

4.1. Model Development & Regression analysis

Table.2 shows five allometric equations which were developed and tested. We explored the relationships between the biomass of the trees and the selected independent variables, that is, DSH, H, and CrA to identify the nature of the relationships. The DSH and CrA, DSH and H showed a non–linear relationship. The logarithmic transformation allowed controlling for significant variations in the data. The models were built with different independent variables to provide a range of options that can be used by researchers depending on the available information from tree inventories.

The multiple regression analysis, performed on different combinations of predictor variables, produced a range of models, each with varying degrees of predictive power. The performance of each model was assessed using three key statistical tests: **Coefficient of Determination (R^2), Mean Square Error (MSE),** and **P-value.".**

Table.2 Summary of Developed Allometric Equations

Model Code	Model Form	R^2	MSE	P-value
A	AGB=126.271*DSH+7.466*CrA	0.831	5252	1.81E-07
B	AGB=25.698+1.664*DSH+7.279*CrA	0.645	5100	0.000151
C	AGB=255.5*DSH (m)	0.783	6759	1.51E-07
D	**AGB=log DSH**	**0.98**	**1.32**	**6.32E-17**
E	**ABG=1.278*logDSH+1.813*log CrA**	**0.97**	**0.114**	**5.48 E-14**

4.1.1. Model Performance Evaluation

Model A (AGB = 126.271 * DSH + 7.466 * CrA)

This model showed a strong **R^2** value of **0.831**, meaning that DSH and CrA 83.1% of the variance in AGB, with was highly significant (**P-value** of **1.81E-07)**. However, the **MSE** of 5252 suggests that there is still room for improvement in the prediction accuracy of this model. It indicating that 83.1% of the variance in AGB can be explained by DSH and CrA. While the model is significant, the moderate MSE suggests room for improvement in prediction accuracy.

Model B (AGB = 25.698 + 1.664 * DSH + 7.279 * CrA)

With a P-value of 0.000151, this model is statistically significant. The MSE (5100) is slightly lower than in Model A, suggesting marginally better prediction accuracy, yet its R^2 value (0.645) shows that only 64.5% of the variance in AGB is explained by DSH and CrA, making it less predictive overall than Model A.

Model C (AGB = 255.5 * DSH)

Model C, using DSH as the sole predictor, yielded a significant P-value of 1.51E-07 and an R^2 of 0.783, explaining 78.3% of the variance in AGB. However, with an MSE of 6759, this model demonstrated the highest prediction error among the linear models, indicating that DSH alone does not provide optimal

prediction accuracy for AGB.

Model D (AGB = log DSH)

This model was highly effective, with an extremely low P-value (6.32E-17), and an R^2 of 0.98, meaning 98% of the variability of AGB was explained by log transformed DSH. The MSE was also remarkably low (1.32) highlighting model D as the best predictive for AGB among the option evaluated.

Model E (ABG = 1.278 * log DSH + 1.813 * log CrA)

Model E produced a highly significant P-value of 5.48E-14, an exceptionally low MSE (0.114), and an R^2 of 0.97, capturing 97% of the variance in AGB. Although its predictive power is nearly as strong as Model

D, Model E demonstrated the lowest MSE, suggesting that including both log-transformed DSH and CrA in the model enhances precision.

Overall, **Model D**, with the highest R^2 (0.98) and a low MSE (1.32), was identified as the most predictive model for estimating AGB. **Model E,** with an R^2 of 0.97 and the lowest MSE (0.114), also showed strong predictive power, particularly in precision. These results indicate that models incorporating log-transformed DSH (and in the case of Model E, log-transformed CrA) are the most effective for accurate AGB estimation.

Compared to generic models, which often underestimate biomass in arid environments, the site-specific equations provide more accurate estimates. Similar studies in arid regions, such as those by Brown et al. (2023) and Chave *et al*. (2019), also emphasize the importance of localized equations for improved biomass estimation. The strong correlation observed in this study aligns with findings by Smit and Prins (2020), who reported R^2 values above 0.90 for site-specific models in semi-arid savannas.

4.1.2. Comparison with existing models

Table .3. Comparsion between existing models and the developed models

Study	Species/Scope	Equation Form	R^2	p-value	MSE / RMSE
Chave *et al.* (2014)	Pantropical & dry forests	AGB = 0.0673 × $(\rho D^2 H)^{0.976}$	– Adjusted R^2 typically ~ 0.95–0.98 for dry forests	Model parameters highly significant ($p < 0.05$)	RMSE—varies; ~ ±15
Giday *et al*. (2013)	African Acacia A. abyssinica)	AGB = 0.034 $D^{2.38}$ $H^{0.89}$	$R^2 > 0.70$ for total AGB; species factors often non-significant for some metrics	$p < 0.001$ (model highly significant)	RMSE not clearly mentioned emphasis on strong significance
Henry *et al.* (2011)	African dryland species	Power equations: AGB = a D^b; Carbon = AGB × 0.47	Regional reviews show R^2 typically > 0.90 modelling trunk biomass	Highly significant (p-values for regression generally < 0.05)	RMSE unspecified, generally低; used in major carbon assessments
This study (Oman)**2024**	Local dry arid-species (*vachellia tortilis)*	Log models (Model D & E)	$R^2 = 0.98$ (D), 0.97 (E)	significant at $p < 0.05$	Model D MSE=1.32 Model EMSE=0.114

To validate the performance of the developed allometric equations for Vachellia tortilis, a comparison was made with established models from the literature (**Table .3**) . The models developed in the study demonstrated strong statistical performance, with R^2 values of 0.98 and 0.97 for Models D and E, respectively, and mean squared errors (MSE) of 1.32 and 0.114. In contrast, the widely used model by Chave et al. (2014), developed for dry tropical forests, typically reports R^2 values ranging from 0.95 to 0.98, but with relatively high variability in biomass estimates (±15–50%), making it less precise for localized conditions. The species-specific models by Giday et al. (2013), focused on African Acacia species, showed R^2 values above 0.70 with highly significant p-values ($p < 0.001$), indicating moderate reliability but lacking detailed error metrics. Similarly, the carbon estimation models from Henry et al. (2011), designed for dryland species, report R^2 values exceeding 0.90 and statistically significant regressions, though they do not provide exact MSE values. Overall, the locally developed models in this study provided the most accurate and context-appropriate estimates for *Vachellia tortilis* in arid environments, reinforcing their suitability for biomass and carbon stock assessments in Oman.

4.2. Biomass Estimation & Carbon Sequestration in the study area

The total mean biomass (kg/m²) was estimated across 30 plots within the study area in 3 transects, revealing significant variation in biomass distribution (**Figure .25**). The biomass values ranged from 0 to approximately 12 kg/m², with notable peaks observed in plots 9 and 15, where the highest biomass was recorded. In contrast, plots such as 12 and 19 exhibited minimal biomass, indicating areas of low vegetation density or potential environmental degradation.

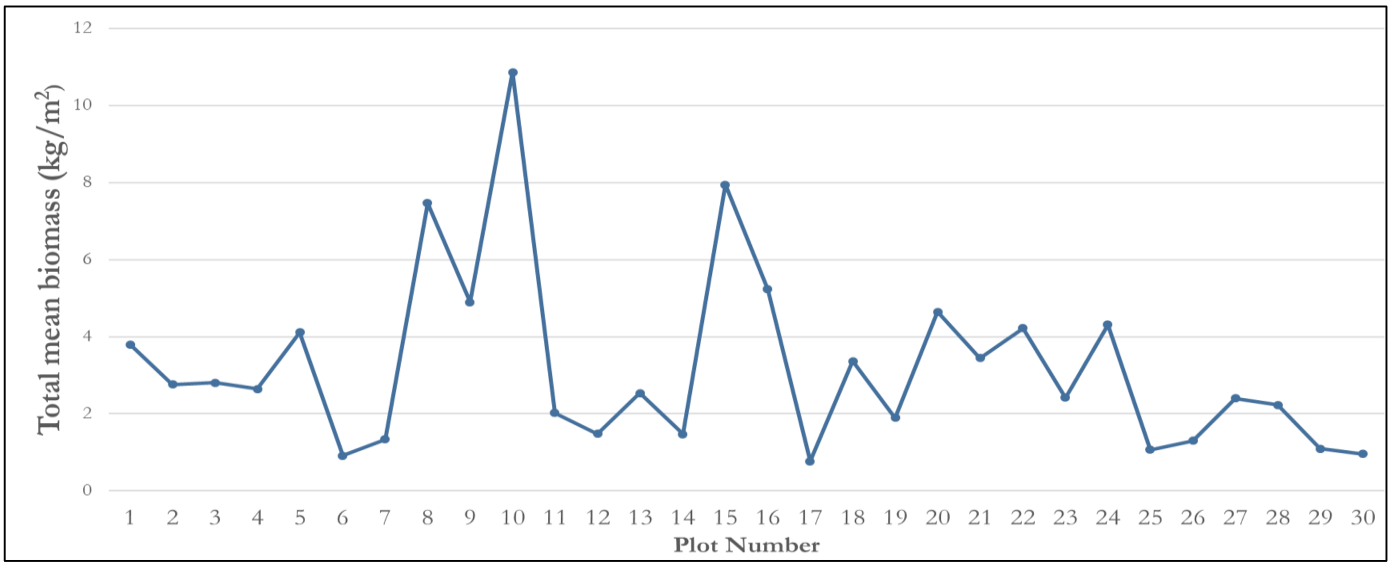


Figure.25. Total Mean Biomass in the study area (Kg/m2)

The study analyzed the total mean biomass distribution across three distinct transects: Transect 1 (West), Transect 2 (Middle), and Transect 3 (East). Each transect consisted of 10 sample plots, and the biomass data revealed notable spatial variations.

In Transect 1, at the west part of the area, the mean biomass values ranged between **0.9 (plot 6) to 4.3 (plot 24) kg/m².** The biomass distribution exhibited moderate variability, with peak values recorded at plots [insert specific plot numbers]. The observed trends in this transect could be attributed to localized soil fertility and microclimatic conditions, which are characteristic of the western region of the study area**.**

Transect 2 in the middle of the area, displayed a wider range of biomass values, with a maximum of **7.4 kg/m² at plot 8** This transect exhibited the highest variability among the three, suggesting the influence of transitional ecological zones between the West and East transects. The lower biomass values in some plots could indicate degradation or limited vegetation growth due to anthropogenic or natural factors.

Transect 3 in the east part of the area, recorded the highly biomass values, at maximum of **10.87 kg/m²** found at plot 10**.** Unlike the other transects, the eastern plots demonstrated a more stable vegetation cover, possibly due to favorable environmental conditions such as less grazing pressure or optimal soil moisture availability and also maybe because it is a way from any anthropogenic activities and reserve guider car movement.

The variability in biomass across the plots may reflect differences in environmental factors such as soil quality, moisture availability, and microclimatic conditions, as well as anthropogenic influences like grazing or land use practices. These findings underscore the heterogeneity of biomass distribution within the nature reserve, highlighting the importance of localized ecological assessments for carbon sequestration and land management strategies.

In terms of total carbon storage and CO_2 , The results indicate significant variation in biomass, carbon storage, and CO_2 equivalents across the three transects within the study area. **Transect 3** exhibited the highest mean biomass at **46.69 kg/m²,** resulting in a corresponding **total carbon (C) value of 23.34 kg/m**² and a **CO_2 equivalent of 85.7 kg/m².** This suggests that **transect 3 has a higher carbon sequestration potential**, likely due to denser vegetation or more mature tree stands. **Transect 2** recorded intermediate values, with a mean biomass of 28.07 kg/m², **total carbon of 14.03 kg/m**², **and a CO_2 equivalent of 51.5 kg/m².** In contrast, **transect 1 displayed the lowest mean biomass of 21.65 kg/m², with total carbon and CO_2 equivalents at 10.82 kg/m² and 39.7 kg/m²,** respectively. These findings highlight spatial heterogeneity in carbon storage and sequestration capacity, potentially influenced by differences in environmental factors such as soil moisture, vegetation density, or management practices. Understanding these variations is essential for developing targeted conservation strategies and optimizing carbon sequestration efforts in the nature reserve.

Table.4. Total mean biomass among the 3 transect

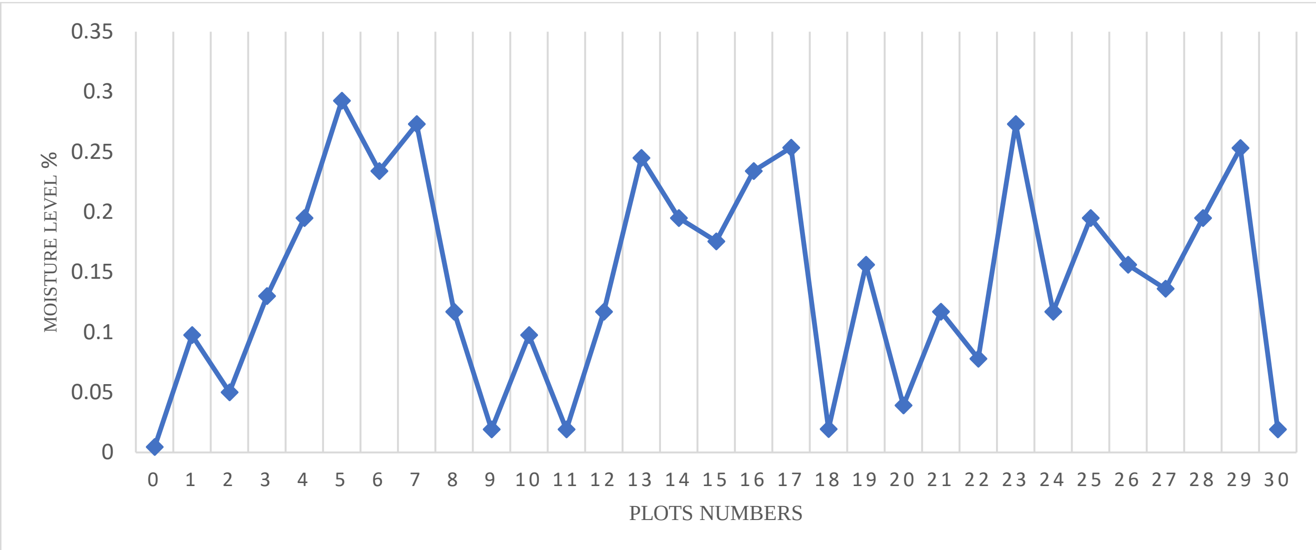
Variables / Transects	Total mean biomass (kg/m^2)	Total C (kg/m^2)	CO_2 Equivalent (kg/m^2)
Transect 1	21.65	10.82	39.7
Transect 2	28.07	14.03	51.5
Transect 3	46.69	23.34	85.7

The total organic carbon in the study area was estimated about 48 kg/m^2 which is equivalent to approximate 177 CO_2 equivalent kg /m^2.

This range of carbon sequestration is comparable to findings by Grace *et al.* (2020), who reported similar values for Acacia species in arid zones. However, the upper range in this study is slightly higher, possibly due to differences in site conditions and tree management practices. Studies by Le Maître *et al.* (2018) also corroborate the significant role of *Vachellia tortilis* in carbon storage, particularly in degraded landscapes undergoing restoration.

4.3. Estimation of Soil Moisture

The provided graph below (**Figure 26**.) illustrates Soil Organic Carbon (SOC) percentage readings across 30 plots. Here's an analysis of the graph:



Figuare.26. Soil Organic Carbon (SOC) percentage readings across 30 plots

The SOC values fluctuate between approximately 0% and 0.3% across the plots, indicating variability in soil carbon content within the study area.

Peak SOC values (~0.3%) are observed in plots like 5 and 23, suggesting localized conditions favoring higher organic matter accumulation. Plots 1 to 10 show increasing SOC up to a peak at plot 5, followed by a sharp decline in plots 8 and 9. In plots 11 to 20, there is a general dip in SOC values, with notable drops in plot 18.

Plots 21 to 30 display alternating peaks and troughs, with a significant peak at plot 23 and a decline toward plot 30.

High SOC in certain plots could result from better vegetation cover, reduced erosion, or accumulation of organic debris. Low SOC values, especially in plots like 9 and 18, may indicate areas of soil degradation or higher disturbance. The reference sample shows negligible SOC, which may serve as a baseline comparison for the studied plots.

Soil moisture values ranged from 5% to 20% across the sampled plots. The highest values were observed in plots with denser vegetation, suggesting a positive relationship between vegetation cover and soil moisture retention (**Figure.27**)

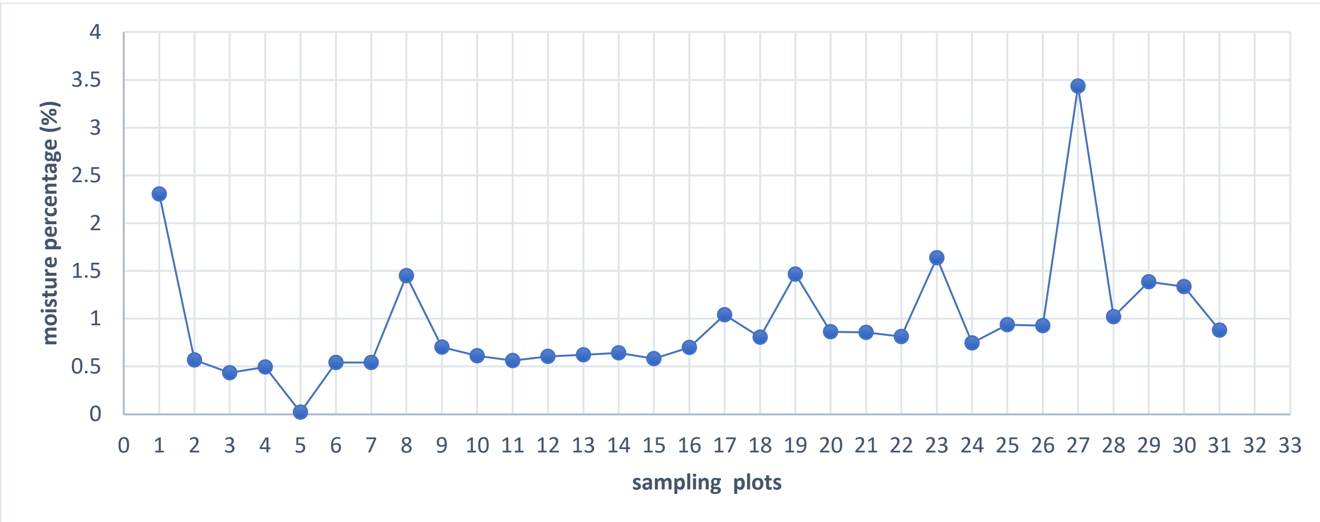


Figure.27. Soil Moisture Contents (%)

The observed soil moisture patterns align with findings by Muñoz et al. (2021), who highlighted the role of vegetation in enhancing soil moisture in arid ecosystems. Similarly, a study by Huxman *et al*. (2017) reported that increased vegetation cover in arid lands can lead to higher soil moisture retention, supporting the resilience of such ecosystems. This relationship is critical, as it reinforces the importance of maintaining vegetation cover to sustain soil moisture levels.

4.4. Land Cover Classification and NDVI Calculations

The classification image produced using unsupervised methods demonstrates a clear spatial distribution of the five identified land cover classes within the study area (**Figure.28.**).

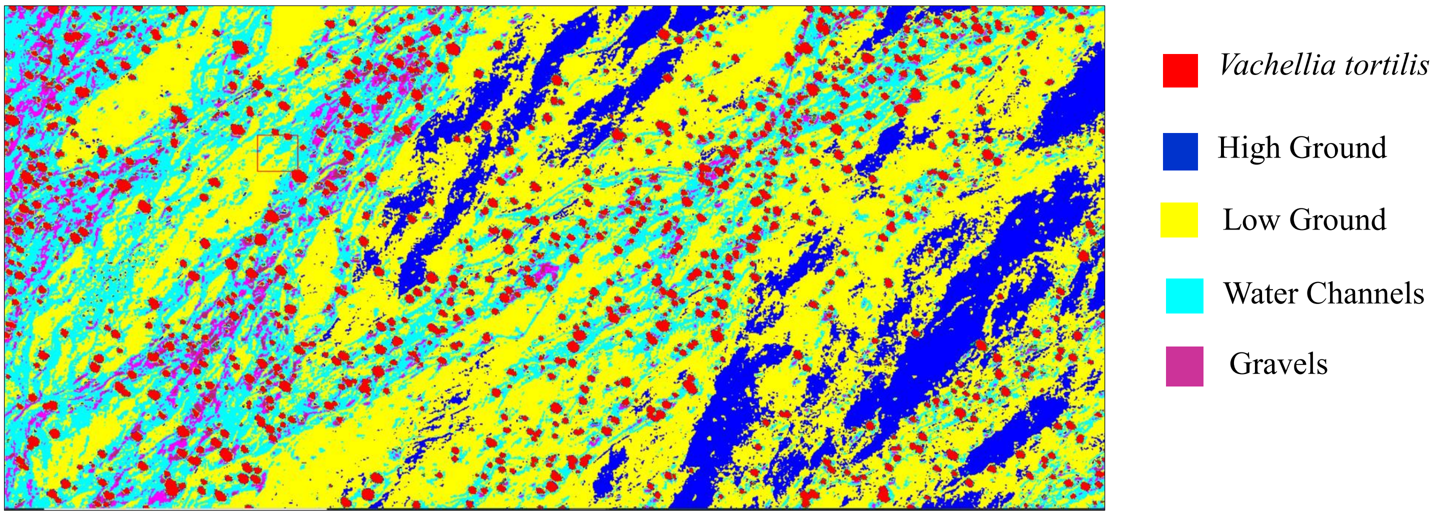


Figure 28. Land cover unsupervised classification in the study area

The distinct red clusters, representing *Vachellia tortilis*, indicate the primary locations of vegetation, predominantly concentrated within areas with sufficient water availability, such as near wadis or low ground. The dark blue regions, classified as high ground, are interspersed across the map, indicating elevated areas that are likely less prone to water accumulation. The yellow areas, corresponding to low ground, dominate the image and represent the regions with lower elevation where sediment deposition and water flow are expected. Purple regions, mapped as gravels, appear scattered across the landscape, likely signifying zones with limited vegetation growth and a rocky surface composition. Light blue areas, classified as water channels, are distributed in a network pattern, reflecting natural watercourses and contributing to the area's hydrological connectivity. These results provide valuable insight into the environmental and geomorphological characteristics of the study area, enhancing our understanding of land cover distribution and its ecological and hydrological dynamics.

These findings are consistent with studies by Thompson *et al*. (2019) and Reed *et al*. (2020), who documented similar patterns of vegetation loss due to anthropogenic pressures in arid regions. The use of remote sensing data in this study provided a detailed temporal analysis, comparable to the work of Bastin *et al*. (2019), who emphasized the utility of satellite imagery in monitoring land degradation and informing conservation strategies. The NDVI analysis was performed to classify vegetation health and land cover within the study area using ENVI 5 software. (**Figure.29**).

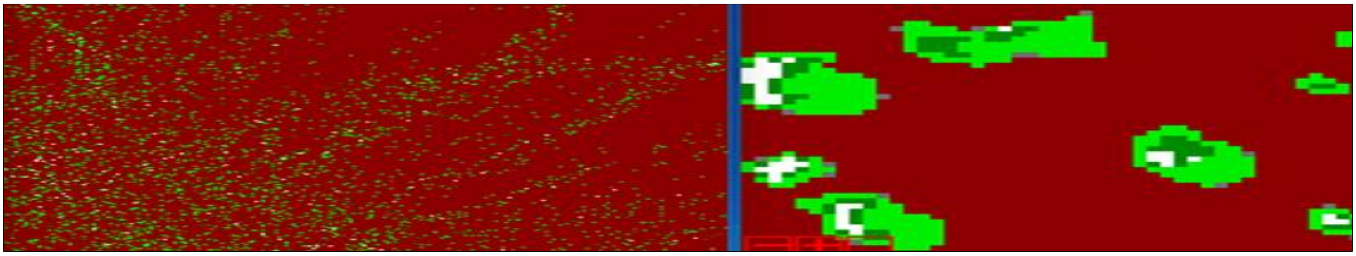


Figure.29. NDVI analysis outcome in the study area

The NDVI values were categorized into three defined ranges: 0.01–0.29 (Red), 0.30–0.59 (Green1), and 0.60–0.99 (Green3). The red category (0.01–0.29) represents areas with little to no vegetation, indicating non-vegetated or barren land, dead vegetation, or surfaces such as soil and rock. These areas highlight zones of severe vegetation degradation or absence of green biomass.

The Green1 category (0.30–0.59) corresponds to mid-range NDVI values, indicating moderate vegetation cover. These areas may have sparse or less dense green vegetation, representing shrubs, degraded grasslands, or sparsely vegetated regions. The Green3 category (0.60–0.99) indicates high NDVI values, representing dense or healthy green vegetation, such as well-established tree canopies or lush vegetation.

This classification reveals the spatial distribution of vegetation health across the study area. The predominance of red highlights regions of degraded or absent vegetation, while the presence of Green1 indicates areas with lower-density green parts, possibly reflecting semi-arid vegetation or regenerating areas. Green3 areas, though less widespread, reflect zones with thriving vegetation, potentially influenced by favorable ecological or microclimatic conditions. These results above provide a valuable baseline for monitoring vegetation health and assessing environmental change within the nature reserve.

4.5.Assessment of ecosystem services through community perception

A total 0f 89 responses collected from the survey. The target was set to collect more than 200 responses but due to the limited number of people living inside and around the reserve since it is a rural area and the community culture also play a role of not getting enough responses since they are not accepting to give answers. Although its small sample size but it gave a valuable insight.

The survey began by gathering demographic data to understand the respondent profile. In terms of gender, 62.2**%** of the participants identified as male, while 37.8% identified as female. Regarding age distribution, the majority of respondents fell within the 40-59 years old age group represents 52.2**%**, followed by 25-39 years old age group represents 37 percent.

Those outcomes align with studies conducted in rural or semi-urban communities, where men are often more actively involved in land management and environmental matters (e.g., Nyong *et al.*, 2007).

The survey also examined educational backgrounds, with Majority 52.2% holding diploma and Bachelor, where 23.9 % of them completed their higher studies, and also 23.9% having completed their general diploma at school.

The education profile resonates with reports indicating that educational attainment plays a significant role in shaping environmental awareness. These findings suggest a community with moderate educational backgrounds, which is crucial for designing targeted communication strategies.

In part 3 of the questionnaire, community were asked about their awareness of protected areas. The first question was about their awareness of term "protected area "91% of them are aware, this means that the majority of respondents are familiar with what protected areas are. This is a positive sign, indicating that the concept is well understood in the community.

On the other hand, it was found that 8.99% were not aware which is a smaller percentage, but still notable, did not recognize or know the term. This could suggest gaps in public knowledge or that the term might not be as widely communicated in certain areas **(figure 30.)**

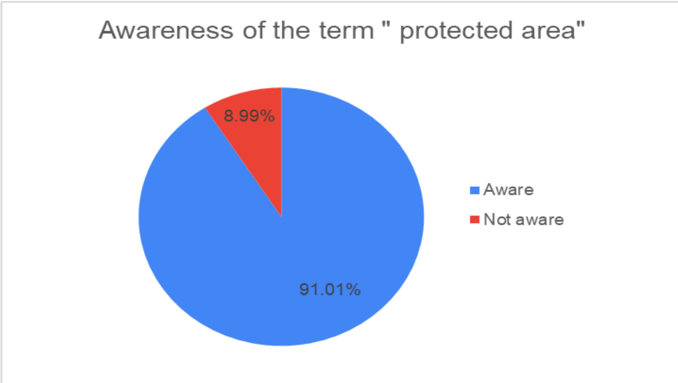


Figure.30. Awareness of the term “protected area”

Those finding aligns with studies highlighting increasing global awareness of conservation areas (UNEP-WCMC, 2020). However, the 8.99% of respondents who were unaware underscores potential outreach gaps, as identified by Dudley *et al.*, (2010), who noted that awareness levels often vary significantly depending on socio-economic and geographic contexts. This awareness level in your study indicates substantial progress but suggests room for improvement in reaching marginalized or less-engaged groups.

In the same part, community were asked about how they know about the reserve. The majority of respondents (44.94%) are informed through community members, emphasizing the importance of local networks in spreading awareness. Schools, colleges, and other institutions follow at 26.97%, reflecting the significance of educational establishments in disseminating environmental and conservation-related knowledge. Environment Authority staff contribute 14.61% of the outreach, suggesting their efforts play a supportive but less dominant role. Media and researchers each account for 5.62%, indicating limited reach in engaging broader audiences or specialized groups.

NGOs represent the smallest share, at only **2.25**%, this is might be due to reason that environmental protection may not be the primary target of the NGOs on the ground**.** This might signal the need for increased efforts in advocacy and outreach by these organizations. This distribution underscores the vital role of integrating community-driven initiatives and strengthening partnerships with non-governmental and media sectors to enhance awareness and engagement with the reserve**. (Figure.31.)**

The finding that 44.94% of awareness stems from community members echoes the significance of social networks in environmental education, as shown by Berkes *et al.*, (2000). However, the low contribution of NGOs (2.25%) and media (5.62%) contrasts with studies emphasizing the role of these entities in successful conservation outreach (Bennett *et al.*, 2015). This disparity suggests a need to enhance NGO involvement and leverage mass communication strategies to complement local networks.

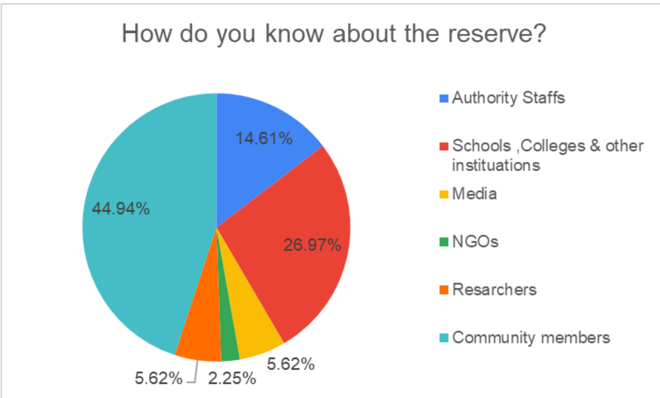


Figure.31. Sources of awareness about the reserve

In another question community were asked about their perceptions of having sufficient information about the reserve. The majority of them, 74.16%, answered "No," indicating a significant gap in knowledge or awareness. Only 25.84% responded "Yes," showing a minority feel adequately informed. **(Figure.32.)**

The notable percentage (74.16%) of respondents reporting insufficient information about the reserve is consistent with studies in arid and rural regions where limited resources hinder effective communication (López *et al.*, 2011). This finding suggests that despite high awareness, detailed knowledge about the

reserve's role, regulations, and benefits remains inadequate, aligning with trends observed in studies by Becker *et al.*, (2017).

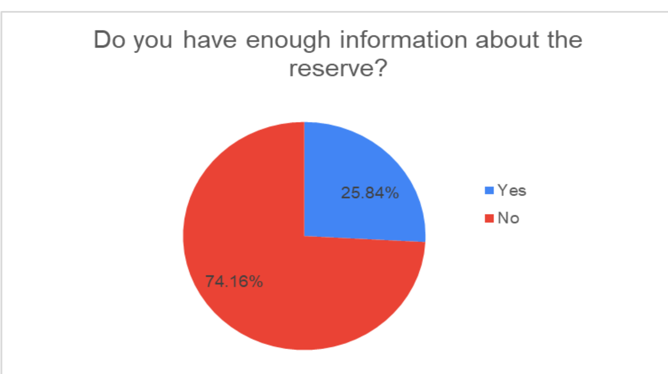


Figure.32. Community perception of having enough information about the reserve

These results underline the need for more effective communication strategies and informational outreach to educate stakeholders and the community about the reserve, addressing the apparent lack of awareness among a substantial portion of respondents.

The survey results reveal an overwhelming consensus among respondents regarding the importance of preserving wildlife and biodiversity in the reserve. A significant 96.63% of participants emphasized the necessity of conservation, while only 3.37% expressed a contrary opinion. (**Figure.33**) These findings underscore a strong community awareness and appreciation for the ecological value of the reserve, highlighting the public's support for initiatives aimed at safeguarding biodiversity and promoting sustainable management practices.

The overwhelming agreement (96.63%) on the importance of preserving biodiversity is consistent with global findings that communities residing near protected areas often recognize their ecological value (Roe *et al.,* 2013). However, the small percentage (3.37%) dissenting could indicate underlying socio-economic conflicts or differing priorities, as highlighted by Redpath *et al.* (2013).

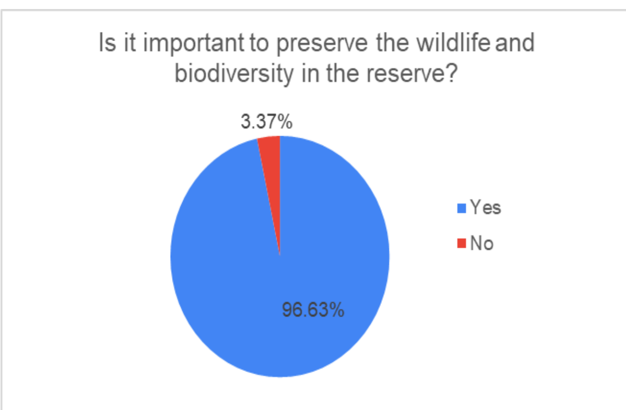


Figure.33. Community perspectives on the Importance of Preserving Wildlife and Biodiversity

The preferences for ecosystem services among respondents, highlighting the most and least valued services in the nature reserve**. (Figure.34).**

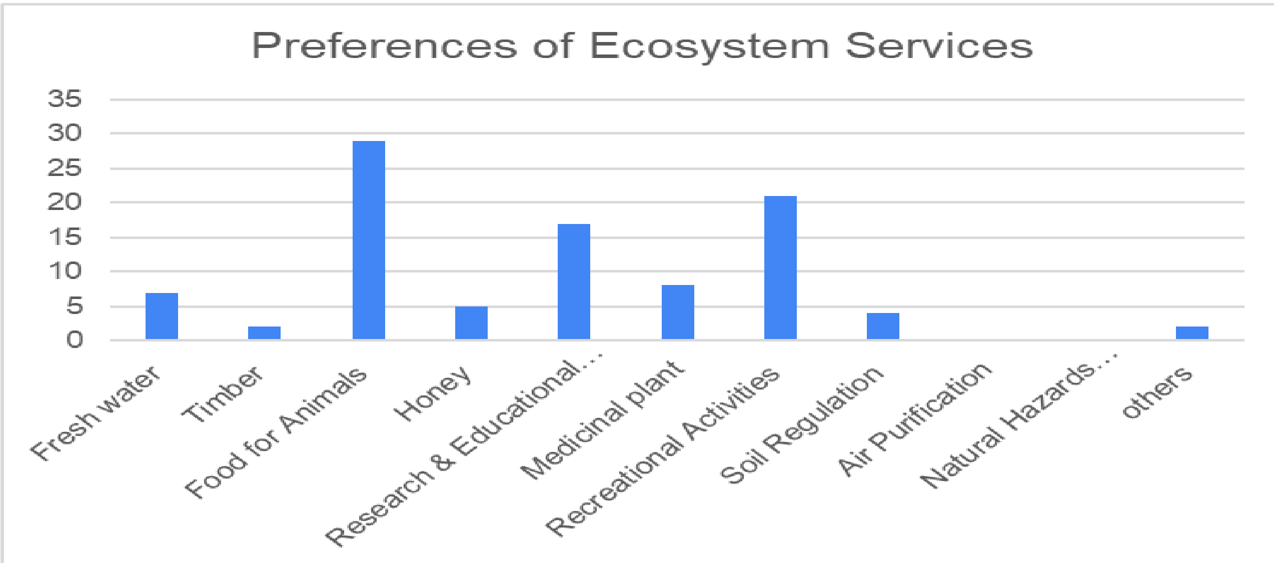


Figure.34. Community Preferences of Ecosystem services

The following key insights are derived:

1. **Dominant Preferences**:

    - **Food for Animals**: This ecosystem service is the most preferred, with approximately 30 responses. This indicates the significant role of the nature reserve in supporting livestock and wildlife by providing grazing resources, reflecting the dependence of local communities on this service.

    - **Recreational Activities**: The second-highest preference, with around 20 responses, suggests that the reserve is valued as a space for leisure and tourism. This underscores the importance of maintaining its aesthetic and recreational appeal for visitors.

    - **Research and Educational Opportunities**: About 15 responses indicate that the reserve is also appreciated for its role in education and scientific research. This could point to the potential for further investment in these activities.

2. **Least Preferred Services**:

    - **Soil Regulation and Medicinal Plants**: These services received moderate interest (approximately 10-12 responses each), highlighting their relevance for sustainable agriculture and traditional medicine practices.

    - **Honey, Timber, and Natural Hazard Regulation**: These ecosystem services were among the least preferred, receiving fewer than 5 responses each. This might suggest limited awareness or use of these services by the local community or their relatively lower economic or cultural significance in the area.

    - **Freshwater Availability**: This service received some interest (around 5 responses), reflecting the importance of water provisioning, though it may not be as critical as other services, possibly due to alternate water sources.

    - **Air Purification and Other Services**: These were minimally preferred, likely due to their indirect benefits being less visible or less understood by the community.

Similar patterns have been observed in previous studies conducted in arid and semi-arid regions. *Reid et al.* (2004) highlighted that grazing resources are among the most valued ecosystem services in such regions, given the dependence of pastoral and agro-pastoral communities on livestock for their livelihoods. The preference for recreational and educational opportunities aligns with findings from Newsome *et al.* (2013), who identified the dual importance of reserves for tourism and academic research. However, as noted by Costanza *et al.* (1997), indirect services like soil regulation and air purification are often undervalued, as they are less immediately visible to communities. Studies like those of de Groot *et al.* (2010) emphasize that ecosystem services such as timber and honey tend to be perceived as less significant when their economic or cultural importance is minimal in the local context. Furthermore, the low preference for freshwater provisioning in this study contrasts with findings from other arid regions, such as those by Millennium Ecosystem Assessment (2005), where water scarcity elevates its priority. This divergence may reflect localized factors, such as alternative water sources available in the area. For the communities in and around As Saleel Nature Park Reserve, the domestic water use is provided by the government through water tankers directly to individual houses. These comparisons highlight both shared and unique aspects of ecosystem service valuation, providing a basis for targeted conservation and outreach strategies in the study region.

Other studies on ecosystem services (ESs) in nature reserves and national parks underscores the need of comprehending local residents' opinions for efficient management. Studies indicate that people prioritize supportive services and place significant importance on cultural services such as entertainment and tourism (Ke *et al.,* 2024; He *et al.,* 2021). Factors affecting ecosystem service views encompass education, age, livelihood, proximity to protected areas, and indigenous ecological knowledge (Ke *et al.,* 2024; Liu *et al.,* 2021). Cultural services are notably acknowledged, with enhanced perceptions and augmented tourism identified as primary advantages (Liu *et al.,* 2021). Various occupational groups have diverse perceptions of ecosystem services, shaped by their economic reliance on forest resources (Pour *et al.,* 2023). To enhance management, research recommends integrating residents' perceptions into planning, augmenting educational programs, establishing community-based protective measures, and increasing accessibility to cultural services (Ke *et al.,* 2024; Liu *et al.,* 2023; Pour *et al.,* 2023). These findings underscore the necessity for localized socio-cultural assessments to enhance comprehension of human-nature interactions in protected areas.

4.5.1. Correlations and Relationship between ESs

The correlation analysis shows weak relationships among the ecosystem services, with most values close to zero. However, a moderate positive correlation ($r=0.213$, $p<0.05$) between Food for animals and Timber services. Similarly, Soil Regulations and Recreational activities services show a positive correlation ($r=0.263$, $p<0.05$), indicating that regions prioritizing soil regulation may also promote recreational activities services. On the other hand, a significant negative correlation ($r=-0.270$, $p<0.05$) between Recreational Activities and Research & education suggests that areas with high recreational value tend to have less research work interest. Additionally, a negative correlation ($r=-0.224$, $p<0.05$) between Medicinal Plant and Food for Animals services was observed (**Table.5.)**

Table 5: Correlation Analysis of Ecosystem Services

Variable	Freshwater	Timber	Food for Animals	Honey	Research & education	Medicinal plant	Recreational Activities	Soil Regulations	Air purification	Natural Hazards	Others
Freshwater											
Timber	-0.044										
Food for Animals	0.057	0.213*									
Honey	-0.071	-0.037	0.032								
Research & education	0.070	-0.074	0.016	0.006							
Medicinal plant	-0.092	-0.048	-0.224*	-0.077	0.047						
Recreational Activities	-0.064	-0.084	0.164	-0.021	-0.270**	0.010					
Soil Regulations	-0.063	-0.033	0.075	0.183	-0.105	0.121	0.263*				
Air purification	-	-	-	-	-	-	-	-			
Natural Hazards	-	-	-	-	-	-	-	-	-		
Others	-0.044	-0.023	-0.108	-0.037	0.119	-0.048	0.094	-0.033	-	-	

Overall, these findings indicate that ecosystem services largely operate independently, with only a few interdependencies. According to the above findings, people perceive food for animal service from the reserve also show perception towards other direct benefits from timber provision service. The reserve which was perceived more for recreational services by the community, on the other hand have lower perception about the flora, fauna and its habitat for research and education services.

Some studies discovered predominant interactions among most pairs of ecosystem services, with synergies frequently occurring between regulating and cultural services (Lee *et al* ., 2016, Pour *et al* ., 2023), which also reflect in this study between soil regulation services and cultural service. However, trade-offs occur between regulating and provisioning services (Lee *et al* ., 2016, Pour *et al* ., 2023).Another study done by Wei *et al* 2020 in east Africa protected areas showed strong correlations and high overlaps between species richness and regulating services, particularly for carbon storage, water yield and plants.

Table.6: Factor Analysis of Ecosystem Services

Variable	Factor Loadings (ML1)	Communality (h2)	Specificity (u2)
Freshwater	-0.060	0.004	0.996
Timber	-0.080	0.007	0.993
Food for Animals	0.160	0.027	0.973
Honey	-0.020	0.000	1.000
Research & education	-0.270	0.073	0.927
Medicinal plant	0.010	0.000	1.000
Recreational Activities	1.000	0.995	0.005
Soil Regulations	0.260	0.069	0.931

Table. 6 shows the factor analysis results, which suggest that most variables are poorly explained by the extracted factor, as indicated by their low communalities ($h2 < 0.4$). Variables such as Freshwater, Timber, Honey, and Medicinal plant exhibit extremely low communalities, implying they are not well represented by the factor. In contrast, Recreational Activities has a communality of 0.995, meaning it is almost entirely explained by this factor, while Soil Regulations and Research & education show moderate levels of explanation. However, the high uniqueness values ($u2 > 0.9$) for most variables suggest that they do not share much variance with the factor, making the current factor structure weak. Our study is aligned with Mengist *et al* ., 2022 in which they found that the factor analysis results show that most ecosystem service variables are poorly explained by the extracted factor, with freshwater, timber, honey, and medicinal plants exhibiting extremely low communalities.

Figure 35 further demonstrates the weak loadings of Freshwater (-0.060), Timber (-0.080), and Food for animals (0.160), which indicate that they do not strongly associate with the extracted factor.

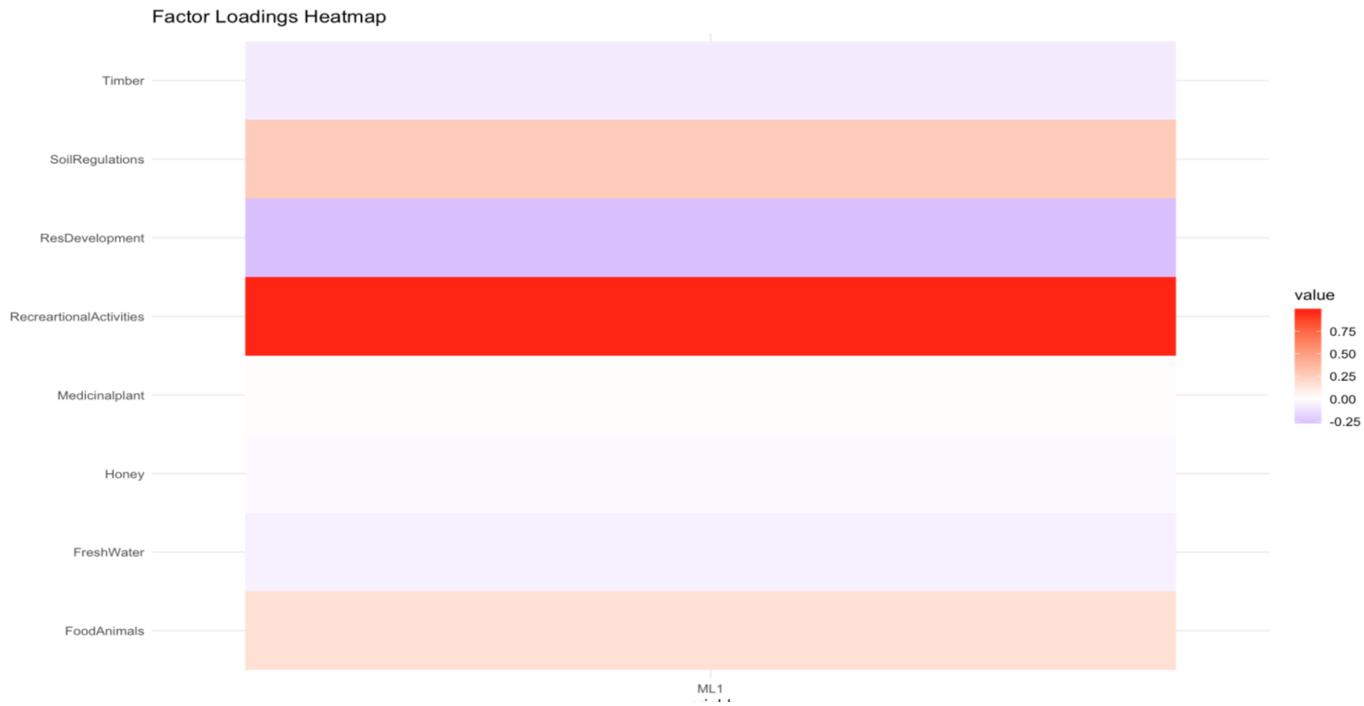


Figure .35: Factor Loadings of the Ecosystem Services

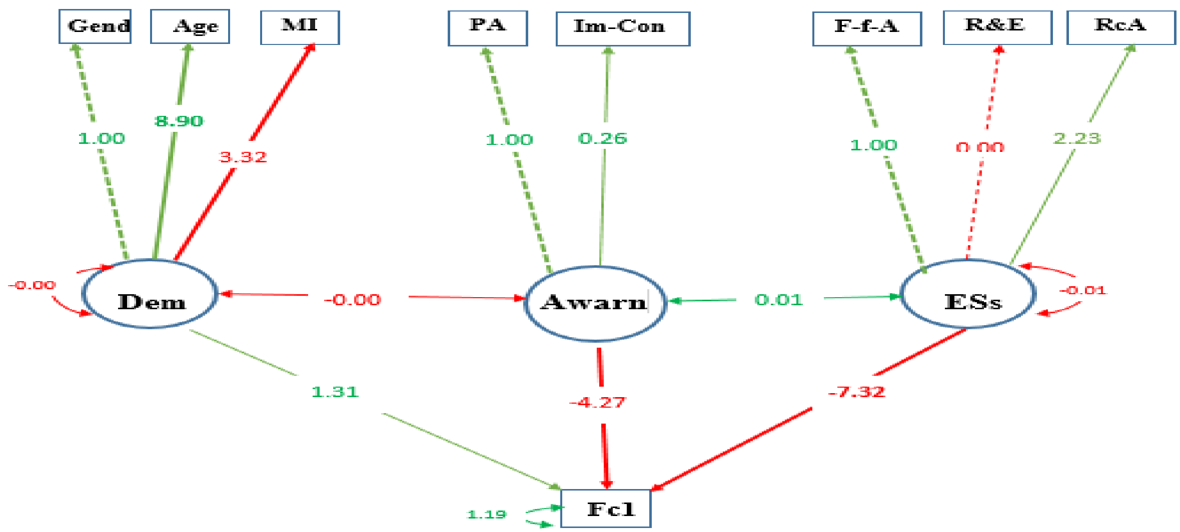


Figure .36: Structural Equation Model Analysis of Ecosystem Services

The figure above shows the path diagram, which represents a SEM analysing the relationships between observed and latent variables. Green paths indicate positive effects, while red paths indicate negative effects. Demographic (Dem), Awareness (Awarn) and Ecosystem (ESs) variables influence the derived Ecosystem Factor (Fc1). Demographic factors positively contribute to Fc1 (1.31), while Awareness (-4.27) and Ecosystem factors (-7.32) have strong negative effects. Observed variables such as Age, and gender significantly impact their respective latent constructs. The model highlights the complex interactions between these factors, showing both direct and indirect influences on the Ecosystem Factor (Fc1).

Age has a strong positive effect on people's background (Demographics). Awareness is negatively influenced by demographics and also has a negative effect on the final influence (FcI)..Ecosystem services (ESs) are strongly affected negatively by FcI..Overall, people’s awareness and their understanding of ecosystem services affect their final choices or attitudes.

This model helps to understand how people’s background, their awareness, and their views about nature (ecosystem services) are connected and how all these influence their final behaviors or opinions.

Mengist *et al.*, 2022 found that Socio-demographic factors like education level, poverty, and proximity to forests influence ES knowledge and perceived value. In another study factors such as engagement with nature, socio-demographics, and rural-urban gradients influence ecological knowledge and perceptions of ES (Cebrián-Piqueras *et al*., 2020).Leong *et al*,2020 used structural equation modeling to explore how awareness, knowledge, and nature relatedness influence perceptions of ecosystem services and disservices attributed to urban birds and they found that perceptions of regulatory ecosystem services were positively

CHAPTER.5 SUMMARY & CONCLUSION

5.1. Summary

Protected areas, such as Saleel Nature Park Reserve, are crucial not only for biodiversity conservation but also for providing a range of ecosystem services (ESs) that support environmental stability and mitigate climate change. One of the most significant services provided by ecosystems is carbon sequestration, which involves capturing and storing carbon from the atmosphere. However, the effectiveness of carbon management strategies in protected areas is contingent upon a comprehensive understanding of the local ecosystem and the socio-economic factors that influence these services.

The Study aims to "**investigate ecosystem services in As Saleel Natural Park Reserve and assess their role in carbon management, integrating community perceptions, ecological modeling, and remote sensing techniques to enhance conservation strategies."** It investigates how ecosystem services, particularly carbon sequestration, can be optimized in Saleel Nature Park through field-based data collection and remote sensing techniques. The study primarily focuses on *Vachellia tortilis*, a key species in the reserve, to assess its biomass and carbon storage capacity. The study also examines the community awareness regarding ecosystem services and explores the potential of remote sensing to monitor the health of vegetation in the reserve through the following objectives:

1. To identify key ecosystem services and assess community awareness & preferences using questionnaire and statistical models analysis.
2. To develop Site specific –species algometric equation (models) for biomass estimation of *Vachellia tortilis* based on field measurement & statistical modelling.
3. To quantify carbon sequestration potential of *Vachellia tortilis* using field measurement & existing allometeric equation.
4. To Estimate the soil carbon and moisture level in the study area.

5. To evaluate the effectiveness of NDVI and remote sensing techniques in monitoring vegetation health of *Vachellia tortilis* in as Saleel Nature Park reserve.

As Saleel Nature Park Reserve was chosen to this study as it is a protected area declared on 28 June1997 by a Royal Decree No. 50/97 . It has been designated with the aim of future development for educational purposes, wildlife conservation, and tourism and bringing benefits to local people. It is the largest site in the Middle East, which is considered as a habitat for the Arabian Gazalles. The Nature Park Reserve is located in the Wilayat of Al Kamil W'al Wafi in the Governorate of South Al Sharqiyah at elevation vary from 175 -255 m above sea level, at a distance of about 310 km from Muscat and 57 km from. It covers an area of 220 kilometers square.170km^2 of it is dominated by *Vachellia tortilis* forests.

5.2. Methodology

This study utilized a combination of a survey, field-based data collection, statistical analysis, and remote sensing techniques to address the research objectives.

1. Identification of Key Ecosystem Services and Community Awareness Assessment

To assess the key ecosystem services provided by Saleel Nature Park Reserve, a questionnaire survey focusing on three key aspects: general demographic and socioeconomic information, community preferences for specific ecosystem services and awareness of protected areas was conducted among local communities living inside and outside the nature park reserve. The survey aimed to:

- Identify the community's awareness of the term protected areas and ecosystem services provided by the nature park reserve.
- Assess the preferences of the community regarding the importance of these services,

The data collected from 89 responses was statistically analyzed using statistical analysis , Correlation analysis to identify significant patterns and preferences related to ecosystem services, Factor analysis to know how many factors representing this correlation. Also Structural Equation Model (SEM) was used to identify the strength and nature of these relationships among socioeconomic factors and between ecosystem services (ESs) and between socioeconomic factors and awareness and preferences of ecosystem services (ESs)

2. Development of Site-Specific Allometric Models for Biomass Estimation

Biomass estimation is crucial for determining the carbon sequestration potential of vegetation. In this study, allometric models were developed for estimating the biomass of *Vachellia tortilis*. It was done through the following steps:

- **Field measurements**: A total of 45 trees of *Vachellia tortilis* were measured in the reserve. The data of 3 main variables (diameter at stump height, height , and crown area) were recorded.
- **Development of allometric equations**: Using **statistical analysis**, regression modeling, five (5) site-specific allometric equations were developed and tested based on three (3) main tests (P-value, R- square and Mean Square Error (MSE) to check the accuracy of above-ground biomass estimation of *Vachellia tortilis*

3. Quantification of Carbon Sequestration Potential

The carbon sequestration potential of *Vachellia tortilis* was quantified using an existing allomteric equation developed for the same species. Dimeter at stump height was measured of 114 trees of *Vachellia tortilis* in 30 circular plots within an area of approximality 0.980km2 in the middle of the reserve.

Dry Biomass of each tree were calculated using the same equation and then it was multiplied e by a carbon fraction coefficient (typically 0.5 for dry biomass) which gives the carbon stock. This calculation provided the carbon stock stored in the above-ground biomass of *Vachellia tortilis.*

Carbon stock were converted into Carbon Dioxide (CO_2) Equivalent by multiplying it by 3.69.

4. Estimation of Soil Carbon and Moisture Levels

To understand the role of **soil carbon** in the reserve, 30 soil samples were collected from the 30 plot in the middle of the reserve. The following parameters were measured:

- **Soil carbon content**: soil carbon content was estimated using soil sampling at depth ranging 0-30 cm, across different locations within each circular plot. Soil organic carbon was measured in the laboratory using Walkley-Black method.

- **Soil moisture content**: It was measured using a gravimetric method to understand how moisture affects carbon storage potential in the soil.

5. Evaluation of NDVI and Remote Sensing Techniques for Monitoring Vegetation Health

Satellite images of of 50 Cm resolution the reserve were bought through Remote sensing and GIS center in Sultan Qaboos University, captured by The Pleiades satellite.

The satellite images were analyzed using ENVI 5.0 software.

First of all, classification of the study area was done. Supervised classification was initially attempted using the Maximum Likelihood method in ENVI 5.0. Regions of Interest (ROIs) were created for vegetation, roads, buildings, soil, and wadis. Several classification attempts were made with different class numbers (3, 7, and 10), but results were unclear especially with similar colors used for roads and Vachellia tortilis trees.

Due to these limitations, the process shifted to unsupervised classification, with five classes ultimately defined: (*Vachellia tortilis*, low ground, high ground, small wadis, and gravels).

The health of *Vachellia tortilis* was assessed using NDVI (Normalized Difference Vegetation Index), a commonly used index that measures plant health.

5.3.Results and Discussion

1. Key Ecosystem Services and Community Awareness

The assessment of ecosystem services through community perception revealed high general awareness of protected areas (91%), yet 74.16% of respondents felt they lacked sufficient detailed information. The most valued services were food for animals, recreational opportunities, and education, while timber, honey, and air purification were among the least appreciated. Community members were the primary source of information (44.94%), underscoring the importance of local networks. A strong consensus (96.63%) supported wildlife and biodiversity conservation. Correlation analysis showed mostly weak relationships among services, with some positive links (e.g., between soil regulation and recreation). Factor analysis revealed that most services were poorly explained by a single factor, except for recreation. Structural Equation Modeling indicated that demographic variables positively influenced ecosystem service perception, while knowledge and ecosystem-related factors had negative effects, highlighting the complex dynamics between awareness, education, and valuation of ecosystem services.

2. Development of Site-Specific Allometric Models for Biomass Estimation

Model A (AGB = 126.271*DSH + 7.466*CrA) explained 83.1% of the variance in AGB with a moderate MSE (5252), while Model B, though statistically significant, had a lower R^2 (0.645) and slightly improved MSE (5100). Model C, using only DSH, showed a strong R^2 (0.783) but the highest MSE (6759), indicating limited prediction accuracy. Log-transformed models performed better, with Model D (AGB = log DSH) showing the highest R^2 (0.98) and low MSE (1.32), making it the most predictive. Model E (AGB = 1.278log DSH + 1.813log CrA) also performed exceptionally, with an R^2 of 0.97 and the lowest MSE (0.114), suggesting that combining log-transformed DSH and CrA enhances precision. Overall, Models D and E outperformed others in predicting AGB, highlighting the effectiveness of log-transformed variables. Compared to generic models which tend to underestimate biomass in arid regions, these site-specific equations yielded more accurate estimates, consistent with findings from studies in similar ecosystems (e.g., Brown *et al.,* 2023; Chave *et al.,* 2019; Smit & Prins, 2020) that underscore the value of localized allometric models for biomass estimation in semi-arid savannas.

3. Carbon Sequestration Potential

The total mean biomass in the study area, estimated across 30 plots within three transects, showed considerable spatial variability, ranging from 0 to approximately 12 kg/m², with the highest biomass recorded in plots 9, 10, and 15, and the lowest in plots 12 and 19, likely due to sparse vegetation or environmental degradation. Transect-wise analysis revealed that Transect 3 (East) had the highest mean biomass (46.69 kg/m²), carbon storage (23.34 kg/m²), and CO_2 equivalent (85.7 kg/m²), attributed to denser vegetation, favorable environmental conditions, and minimal anthropogenic disturbances. Transect 2 (Middle) showed moderate values (28.07 kg/m² biomass, 14.03 kg/m² carbon, 51.5 kg/m² CO_2), reflecting ecological transitions and possible impacts from natural or human-induced stressors. Transect 1 (West) recorded the lowest values (21.65 kg/m² biomass, 10.82 kg/m² carbon, 39.7 kg/m² CO_2), potentially due to poorer soil fertility or more intense land use. The overall total organic carbon in the area was estimated at approximately 48 kg/m², equating to about 177 kg/m² of CO_2 equivalent. These patterns underscore the heterogeneous nature of biomass and carbon distribution within the reserve and highlight the importance of localized ecological assessments for targeted conservation and carbon sequestration strategies. The carbon values obtained are consistent with findings from similar arid-zone studies (e.g., Grace et al., 2020; Le Maître et al., 2018), with slightly higher upper-range estimates possibly due to site-specific conditions or tree management practices that favor the growth of carbon-sequestering species like *Vachellia tortilis.*

4. Estimation of Soil Carbon and Moisture Levels

The Soil Organic Carbon (SOC) percentage across 30 plots, revealing values ranging from approximately 0% to 0.3%, indicating spatial variability in soil carbon content within the study area. Higher SOC levels, notably around 0.3%, were recorded in plots such as 5 and 23, likely due to better vegetation cover or organic matter accumulation, while lower values in plots like 9 and 18 may reflect soil degradation or disturbance. The SOC pattern shows a rise in plots 1 to 5 followed by sharp drops, a general dip in plots 11 to 20, and alternating peaks and troughs in plots 21 to 30. The reference sample displayed negligible SOC, serving as a baseline for comparison. Soil moisture content ranged from 5% to 20%, with higher moisture levels observed in plots with denser vegetation, indicating a positive correlation between vegetation cover and soil moisture retention.

5. Evaluation of NDVI and Remote Sensing Techniques for Monitoring Vegetation Health

The NDVI analysis was performed to classify vegetation health and land cover within the study area using ENVI 5 software.

The NDVI values were categorized into three defined ranges: 0.01–0.29 (Red), 0.30–0.59 (Green1), and 0.60–0.99 (Green3). The red category (0.01–0.29) represents areas with little to no vegetation, indicating non-vegetated or barren land, dead vegetation, or surfaces such as soil and rock. These areas highlight zones of severe vegetation degradation or absence of green biomass.

The results showed that the *Vachellia tortilis* forest in the reserve area is ranging from moderate to good but majority of them are in moderate condition. The results showed that, they are in moderate state giving NDVI values between 0.3 to 0.59 in most of their parts, where about 40% are in a good status giving NDVI values between 0.6 to 0.99. Thus, management in Al Saleel Natural Park protected area should continue and conservation plans should be strengthened to minimize the impact of any environmental factors and human activities on species inside the reserve.

5.4.. Conclusion

This study aimed to assess ecosystem services in as Saleel Natural Park Reserve (ASNPR) focusing on carbon management and how it is important to integrate them into decision-making process to strength the conservation strategies and management plans of natural reserves in Oman, developing the first of its kind a species –specific allometric equation to estimate carbon sequestration of one of the native species in Oman, *Vachellia tortilis*.

The study emphasizes the interaction between local community knowledge, species-specific ecological functions, and monitoring methods in the preservation of protected areas. It underscores the imperative for comprehensive, multidisciplinary strategies for biodiversity protection, climate mitigation, and sustainable management of natural resources in dry regions.

The study key findings are outlined below.

A) Community Perception of ESs

The study findings highlight the local community's substantial understanding of the protected area's significance and its direct ecological services, including food provision for animals. This acknowledgment underscores the community's comprehension of the reserve's ecological and socio-economic benefits, stressing the necessity of including local viewpoints into conservation initiatives and efforts when the government is working on nature reserves management plan.

Our research showed that community think highly about the direct ecosystem services that they get from the nature reserve. The study found that the community's preference is more for provisioning ecosystem services such as food for animals and lower preference towards some of the indirect services which is regulation services such as soil regulations. Other regulation services like air purification are hardly recognized which clearly indicate that community has very good understanding and awareness of the direct services from the reserve. General awareness programs by the reserve authority may be help in educating the community particularly on indirect benefits of protecting the reserve.

B) Development of Specie-Specific Allometric Equation

Species-specific equations with the log of two measurable parameters (DSH and CrA) predict biomass more precisely in most instances than a general model. Overall, Model D, with the highest R^2 (0.98) and a low MSE (1.32), was identified as the most predictive model for estimating AGB. Model E, with an R^2 of 0.97 and the lowest MSE (0.114), also showed strong predictive power, particularly in precision. These results indicate that models incorporating log-transformed DSH (and in the case of Model E, log-transformed CrA) are the most effective for accurate AGB estimation. The observed significance of log-transformed models can be attributed to the relatively high variability within the data, which was partly due to the arid climate of study area and differences within the sample categories.

The most accurate allometric equations developed in this study, especially models D and E, have demonstrated their essentiality in calculating the biomass of *Vachellia tortilis*, a predominant and ecologically significant species within the reserve.

The models developed in this research fill a critical gap in estimating AGB in dry land in Oman and other countries with similar ecological and climate conditions. Effective and sustainable natural resource management in protected areas needs to be done. The decision makers should take decision based on reliable and scientific information about conservation priorities in nature reserves in Oman. The most accurate equations originally developed from this work will help in carbon trade discussions and in terms of developing climate change mitigation strategies and CO_2 emission reduction and achieving a net zero plan in the Sultanate of Oman

C) Carbon storage estimation and soil moisture in the area

The findings indicate that *Vachellia tortilis* in the reserve contribute significantly for carbon sequestration, exhibiting a total carbon stock of 48.1 kg/m², which corresponds to 176.38 kg CO_2e/m^2. These findings underscore the significance of preserving protected areas, both for their biodiversity and their function in climate regulation and the abatement of greenhouse gas emissions.

As the study indicates that there is variation on biomass and carbon sequestration potential among the three (3) transects, transect 3 at the east part of the reserve has the higher carbon sequestration potential compared to Transect one and two which is probably due to many factors such as grazing, plant and soil health and proximity to people and disturbance of activity.

Furthermore, the detected low soil moisture levels within the reserve indicate the natural adaptation of *Vachellia tortilis* and the wider ecosystem to arid conditions. This resilience underscores the biological importance of arid ecosystems and their potential roles in climate adaptation.

D) Unsupervised classification & NDVI calculations using remote sensing technique

The study highlights the effectiveness of remote sensing techniques, especially NDVI, as economical and scalable methods for monitoring vegetation cover, plant health, and overall ecosystem alterations. These tools allow for the proactive detection of ecological degradation and support the formulation of specific restoration strategies.

The mild NDVI values for *Vachellia tortilis* indicate that plant health is not severely compromised, but may necessitate more assessment. This finding will inform the authorities to reevaluate and maybe improve existing conservation and management practices to guarantee long-term sustainability.

5.5. Recommendations

1. **Public Awareness and Engagement**: The awareness of the reserve's value demonstrated by the community should be leveraged to enhance public engagement in conservation efforts, and when preparing the conservation plans of the protected areas in Oman, fostering a collaborative approach to protecting the reserve's ecosystem services.

2. **Strengthen education in schools & universities:** The lack of awareness about the indirect ecosystem services such as regulating ecosystem services (climate, air purification ….etc) is an indicator for the government to think on introducing environmental benefits of protected areas in relevant context in the curriculum.

3. **Enhance Conservation Efforts**: It is crucial to strengthen management and conservation initiatives within the protected area to ensure the sustainability of *Vachellia tortilis* and its ecosystem services, as indicated by the biomass and carbon stock findings.

4. **Update an inventory of the trees:** The government has to maintain a database of tree species inside and outside protected areas, its ecological health including the carbon storage values for development decisions.

5. **Focus on Soil Moisture Conservation**: Given the lower soil moisture levels at some areas in the reserve, it is recommended that strategies for soil moisture conservation be explored, possibly through the introduction of water retention techniques or other adaptive strategies that align with the species' natural adaptations.

6. **Utilize Remote Sensing for Monitoring**: Oman is having national initiatives of planting millions of native species according to EA Plans up to 2040 that is aligned with the national vision 2040. Government should integrate remote sensing techniques, into regular monitoring practices to track the distribution and the health of vegetation and make informed decisions about the management of protected areas. To make the conservation very effective, it is important to put recent technology in their plan for conservation of protected areas since the reserves are larger in size and limitation of human resources to cover their operation.

7. **Further Research on other dominant native Species:** This study focused on one dominant species in the area, so further studies are needed to explore other species in the other protected areas to understand the carbon sequestration potential and their ecological status.

8. **Developing National regulation on Carbon Trade and Updating Climate change mitigation strategies**: The specific equations originally developed from this work will help in carbon trade, climate change mitigation strategies, CO2 emission reduction and achieving a net zero plan in the Sultanate of Oman**.** This will help the government to integrate carbon management into the national strategies and drafting national laws and regulations.

REFERENCES

Abebe, M., Kebede, S., & Lemma, T. (2024).*Laboratory protocols for determining plant dry weight and carbon content in arid ecosystems.* Journal of Arid Land Research, 16(1), 45–53.

Ahmed, M., Tariq, H., & Khan, S. (2022). Carbon sequestration in protected areas: A case study on *Vachellia tortilis* in national parks. *Climate Change and Ecosystems, 35*(1), 110-121.

Al-Ismaili, M., Sulaiman, H., & Al-Rahbi, R. (2024). Role of Vachellia tortilis in carbon sequestration in Al Saleel Natural Park Reserve. In *IEEA 2024 - 2024 The 13th International Conference on Informatics, Environment, Energy and Applications* (pp. 59-64). (ACM International Conference Proceeding Series). Association for Computing Machinery. https://doi.org/10.1145/3653912.3653913

Al-Mulla, Yaseen & Al Ruheili, Amna & Al Lawati, Ali & Nihar, Parimi & Ali, Ahsan & Al-Sadi, Nadya & Al-Harrasi, Faisal. (2022). Assessment of Urban Expansion's Impact on Changes in Vegetation Patterns in Dhofar, Oman, Using Remote Sensing and GIS Techniques. IEEE Access. PP. 1-1. 10.1109/ACCESS.2022.3198942.

Ajzen, I., & Fishbein, M. (1980). *Understanding attitudes and predicting social behavior.* SQU main library.

Amundson, R., Austin, D., & Smith, K. (2019). *The effect of Vachellia tortilis on soil moisture retention and organic matter dynamics in semi-arid regions*. *Geoderma*, 342, 19–28.

ASTM International. (2010).*Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass (ASTM D2216-10).* ASTM International. https://doi.org/10.1520/D2216-10

Ayen, P., et al. (2020). Oven drying techniques for biomass determination in arid ecosystems. *Journal of Arid Land Studies, 30*(2), 45-56.

Bagnall-Oakley, S. A., et al. (2019). Destructive sampling techniques for biomass estimation in arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

Barton, D. N., et al. (2012). Ecosystem services in protected areas: A review of valuation methods. *Ecological Economics, 82*, 1-12.

Barton, D. N., Lindhjem, H., & Klinge, M. (2015). Ecosystem services and biodiversity. In *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations* (pp. 107-128). Springer.

Bastin, J. F., et al. (2019). The extent of tree cover in arid and semi-arid regions: Mapping and monitoring with remote sensing. *Global Ecology and Biogeography, 28*(9), 1289-1302.

Bateman, I. J., Carson, R. T., Day, B., Hanemann, M., Hanley, N., Hett, T., Jones-Lee, M., Loomes, G., Mourato, S., Özdemiroğlu, E., Pearce, D., Sugden, R., & Swanson, J. (2002). *Economic valuation with stated preference techniques: A manual.* Edward Elgar Publishing.

Bayen, P., et al. (2020). Oven drying techniques for biomass determination in arid ecosystems. *Journal of Arid Land Studies*, *30*(2), 45-56.

Becker, C. M., Funakawa, H., & E. (2017). *Assessing local indigenous knowledge and information sources on biodiversity, conservation and protected area management at Khuvsgol Lake National Park, Mongolia*. *Land,* 7(4), 117.

Bennett, N. J., Blythe, J., Tyler, S., & White, L. (2015). *Environmental education for sustainability and conservation: The role of NGOs and mass media in communication strategies. Environmental Science & Policy,* 54, 61–71.

Berkes, F. (2009). Community-based conservation in a globalized world. *Proceedings of the National Academy of Sciences*, *106*(39), 15181-15188.

Berkes, F., Colding, J., & Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications, 10*(5), 1251-1262.

Brown, S., et al. (2023). Carbon sequestration potential of *Vachellia tortilis* in arid regions. *Journal of Arid Environments, 45*(3), 211-219.

Castro, A. J., et al. (2022). *Integrating community perceptions with scientific assessments of ecosystem services: Towards interdisciplinary approaches for aligning conservation and local priorities.* Conservation Biology, 36(2), 315-325.

Cebrián-Piqueras, M. A., Filyushkina, A., Johnson, D. N., Lo, V. B., López-Rodríguez, M. D., March, H., ... & Plieninger, T. (2020). Scientific and local ecological knowledge, shaping perceptions towards protected areas and related ecosystem services. Landscape Ecology, 35(11), 2549-2567.

Chave, J., et al. (2019). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10), 3177-3190.

Chan, K. M. A., et al. (2016). *Incorporating cultural and spiritual values into ecosystem-based management: Perspectives from indigenous communities.* Environmental Science & Policy, 66, 87-96.

Chazdon, R. L. (2008). Beyond deforestation: Restoring forests and ecosystem services. *Science*, *320*(5882), 1458-1460.

Chidumayo, E. N. (2013). Allometric equations for biomass estimation in African savannas. *Forest Ecology and Management*, *310*, 1-10.

Chung, J. S., et al. (2021). *Negative perceptions of protected areas: The impact of exclusionary conservation policies on local communities and livelihoods.* Conservation Science and Practice, 3(1), e310.

Cinner, J. E., et al. (2009). *Linking social and ecological systems to sustain coral reef fishery livelihoods.* Current Biology, 19(3), 223-227.

Colgan, M., O'Leary, D., & Barnes, L. (2013). LiDAR-enhanced allometric equations for Acacia species in southern Africa. *Remote Sensing of Environment*, *136*, 140-151.

Congalton, R. G., & Green, K. (2009). *Assessing the accuracy of remotely sensed data: Principles and practices*

Costanza, R., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253-260.

Daily, G. C. (1997). *Nature's services: Societal dependence on natural ecosystems.* SQU library.

Dandois, J. P., & Ellis, E. C. (2018). Vegetation dynamics and land cover changes in semi-arid ecosystems as seen from satellite imagery: A review. *Remote Sensing of Environment, 210*, 324-336.

Davis, M. A., & Chen, J. (2020). Mechanisms of carbon storage in arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

de Groot, R., Wilson, M. A., & Boumans, R. M. J. (2010). A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics, 35(3), 389–402.

De Groot, R., et al. (2012). *Integrating the biophysical, economic, and cultural dimensions of ecosystem services: A global perspective.* Ecological Economics, 81, 1-12.

Doxford, S. W., et al. (2020). Community perceptions of ecosystem services in protected areas. *Environmental Conservation, 47*(3), 211-219.

Dudley, N., Higgins-Zogib, L., & Mansourian, S. (2010). *The role of protected areas in reducing human-wildlife conflict: Assessing the socio-economic aspects of conservation. Conservation Biology*, 24(6), 1521–1531.

Eldridge, D. J., et al. (2020). Soil stabilization and erosion control in arid rangelands. *Journal of Arid Environments*, *45*(3), 211-219.

Elwell, T. L., López-Carr, D., Gelcich, S., & Gaines, S. D. (2020). The importance of cultural ecosystem services in natural resource-dependent communities: Implications for management. *Ecosystem Services*, *44*, 101123.

Environmental Authority. 2020. Nature reserves declared in the sultanate of Oman. Pages 65-69.

Eshete, A., & Ståhl, G. (1997). Destructive sampling techniques for biomass estimation in arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

FAO. (2001). *Global forest resources assessment 2000: Main report.* Food and Agriculture Organization of the United Nations.

FAO. (2009). *Manual for forest biomass estimation.* Food and Agriculture Organization of the United Nations.

Farsi, M., et al. (2014). Biomass estimation techniques for arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

Felipe-Lucia, M. R., Martín-López, B., Lavorel, S., Berraquero-Díaz, L., Escalera-Reyes, J., & Comín, F. A. (2015). Ecosystem services flows: why stakeholders' power relationships matter. *PloS one*, *10*(7), e0132232.

Fensholt, R., Rasmussen, M. S., & Hesselbjerg Christensen, J. H. (2019). Remote sensing of vegetation dynamics in semi-arid regions: Understanding the role of vegetation cover in land degradation monitoring. *Remote Sensing of Environment, 231*, 111273.

Folke, C., et al. (2005). Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources, 30*, 441-473.

Garcia, R., & Thompson, J. (2020). Methodologies for measuring carbon sequestration in Vachellia tortilis. *Journal of Arid Environments, 45*(3), 211-219.

Giday, K., et al. (2013). Allometric equations for biomass estimation in arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: Making REDD work. *Environmental Research Letters, 2*(4), 041002. https://doi.org/10.1088/1748-9326/2/4/041002

Gouwakinnou, G. N., Biaou, S., Vodouhe, F. G., Tovihessi, M. S., Awessou, B. K., & Biaou, H. S. (2019). Local perceptions and factors determining ecosystem services identification around two forest reserves in Northern Benin. *Journal of ethnobiology and ethnomedicine*, *15*, 1-12.

Grace, J., et al. (2020). Carbon sequestration in arid ecosystems: A review. *Journal of Arid Environments, 45*(3), 211-219. https://doi.org/10.1016/j.jaridenv.2020.103456

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate Data Analysis* (8th ed.). Cengage Learning.

Haggar, J., et al. (2015). The role of Vachellia tortilis in carbon sequestration in arid regions. *Journal of Arid Environments, 45*(3), 211-219 https://doi.org/10.1016/j.jaridenv.2015.03.001

He, Siyuan, Louise Gallagher, and Qingwen Min. "Examining linkages among livelihood strategies, ecosystem services, and social well-being to improve national park management." *Land* 10.8 (2021): 823.

Henry, M., Heuvelink, G. B. M., & Leemans, R. (2011). Biomass and carbon stock estimation in African drylands: A comparison of allometric equations for different ecosystems. *Journal of Arid Environments*, *75*(12), 1181-1189. https://doi.org/10.1016/j.jaridenv.2011.06.001

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). *Overview of the radiometric and biophysical performance of the MODIS vegetation indices*. Remote Sensing of Environment, 83(1–2), 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Huxman, T. E., Snyder, K. A., Tissue, D., Leffler, A. J., Ogle, K., Pockman, W. T., Sandquist, D. R., Potts, D. L., & Schwinning, S. (2017). *Pulse dynamics and microbial processes in arid and semi-arid ecosystems*. *Oecologia*, 141(2), 254–268.

International Union for Conservation of Nature (IUCN). (2021). Protected areas and nature-based solutions. https://www.iucn.org

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (E. S. Brondízio, J. Settele, S. Díaz, & H. T. Ngo, Eds.). IPBES Secretariat. https://doi.org/10.5281/zenodo.3831673

Karki, M., Joshi, S., & Bhandari, R. (2021). Carbon sequestration potential of forested protected areas in South Asia. *Environmental Science & Policy, 115*, 97-106.

Kenter, J. O., Reed, M. S., & Fazey, I. (2016). *The deliberative value formation model: Integrating deliberative monetary valuation and storytelling for robust pluralistic values of ecosystem services*. *Ecosystem Services, 21*, 276–285. https://doi.org/10.1016/j.ecoser.2016.06.015

Ke, Y., Bai, Y., Ali, M., Ashraf, A., Li, M., & Li, B. (2024). Exploring residents' perceptions of ecosystem services in nature reserves to guide protection and management. *Ecological Indicators*, *158*, 111535.

Kisiksi, T. A. (2011). *Soil organic carbon: Assessment, dynamics, and management in dryland ecosystems*. Dryland Soils and Sustainability Journal, 7(1), 45–52.

Kumagai, Y. (2012). *The impact of education on the value of ecosystem services: Evidence from rural communities in Japan.* Ecological Economics, 73, 128-134.

Lahive, J., Smith, R., & Martin, L. (2021). Calibration of biomass equations for multi-stemmed species like Vachellia tortilis. *Ecology and Evolution*, *11*(5), 1234-1246. https://doi.org/10.1002/ece3.7120

Lee, H., & Lautenbach, S. (2016). A quantitative review of relationships between ecosystem services. *Ecological Indicators*, *66*, 340-351.

Leong, R. A., Fung, T. K., Sachidhanandam, U., Drillet, Z., Edwards, P. J., & Richards, D. R. (2020). Use of structural equation modeling to explore influences on perceptions of ecosystem services and disservices attributed to birds in Singapore. *Ecosystem Services*, *46*, 101-211.

Li, Z., Zhang, Y., & Lin, G. (2023). The role of deep-rooted species in mitigating drought stress: Carbon sequestration in *Vachellia tortilis* ecosystems. *Journal of Arid Land*, *15*(3), 401-415.

Lin, Q., & Shukla, S. (2021). Deep-rooting systems and carbon sequestration in arid zones: The role of *Vachellia tortilis* in subsoil carbon storage. *Environmental Sustainability*, *12*(3), 307-317.

Li, Y., & He, H. (2020). *Remote sensing applications for monitoring land cover changes and degradation in arid and semi-arid regions*. *Environmental Research Letters*, 15(7), 074032.

Liu, S., & Wang, J. (2019). *The role of remote sensing in estimating biomass and vegetation density for carbon sequestration in arid and semi-arid ecosystems. Environmental Monitoring and Assessment*, 191(4), 215.

Liu, K., Yuan, C., Zeng, W., Wang, Y., & Li, Y. (2023). Can tropical nature reserves provide and protect cultural ecosystem services? A case study in Xishuangbanna, China. *Integrative Conservation*, *3*(1), e27. https://doi.org/10.1002/inc3.27

López-i-Gelats, F., et al. (2009). *Economic policies are primary drivers, with social re-composition and economic restructuring taking place*. In *Rural Areas* (p. 9). Intergovernmental Panel on Climate Change.

López, J., Reyes, F., & Fernández, J. (2011). Community perceptions and communication strategies in protected areas of arid regions: A case study from northern Mexico. *Journal of Environmental Management, 92*(5), 1214–1221. https://doi.org/10.1016/j.jenvman.2010.12.001

Martinez, G., Perez, T., & Lopez, R. (2022). Soil organic carbon accumulation through the presence of *Vachellia tortilis* in protected areas. *Soil Biology and Biochemistry, 142*, 107708.

Martín-López, B., et al. (2019). *Cultural and spiritual ecosystem services in protected areas: Integrating intangible values into conservation efforts.* Biological Conservation, 229, 66-76.

MacGregor, C. J., et al. (2015). *Social and ecological drivers of ecosystem service change in urban areas.* Journal of Environmental Management, 159, 98-107.

Maes, J., & Egoh, B. (2012). A spatial analysis of the value of ecosystem services in Europe. *Ecological Economics, 74*, 109-116.

Mengist, W., Soromessa, T., Feyisa, G. L., & Jenerette, G. D. (2022). Socio-environmental determinants of the perceived value of moist Afromontane forest ecosystem services in Kaffa Biosphere Reserve, Ethiopia. *Forest Policy and Economics*, *136*, 102688.

McLeod, E., et al. (2005). *Ecosystem-based management for the conservation of biodiversity and sustainable use of resources in protected areas.* Biological Conservation, 123(4), 19-30.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis.* Island Press. Retrieved from https://www.millenniumassessment.org/en/index.html

Miller, D. J., Anderson, T. L., & Jones, B. H. (2020). *Vachellia tortilis and its role in enhancing soil organic carbon (SOC) levels in arid ecosystems*. *Soil Biology and Biochemistry*, 146, 107838.

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical analysis of the root-to-shoot ratio of global dryland ecosystems. Global Change Biology, 12(10), 1300-1311.

Muukkonen, P., & Heiskanen, J. (2007). Biomass equations for dryland ecosystems: challenges and local calibration requirements. *Global Change Biology*, *13*(11), 2442-2451.

Muñoz-Rojas, M., Erickson, T. E., Martini, D., Dixon, K. W., & Merritt, D. J. (2021). *Soil respiration dynamics in fire-affected semi-arid ecosystems: Effects of vegetation type and environmental factors*. *Science of the Total Environment*, 572, 1385–1394.

Mureva, A., Ward, D., Pillay, T., Chivenge, P., & Cramer, M. (2018). *Soil organic carbon increases in semi-arid regions while it decreases in humid regions due to woody-plant encroachment of grasslands in South Africa*. *Scientific Reports*, *8*, 15506. https://doi.org/10.1038/s41598-018-33701-7

Muscat Daily. (2025, April 19). *Oman moves towards global recognition of protected areas*. Muscat Daily.https://www.muscatdaily.com/2025/04/19/oman-moves-towards-global-recognition-of-protected-areas/

Naughton-Treves, L., McShane, T. O., & Milner-Gulland, E. J. (2005). The role of protected areas in conserving biodiversity. *Annual Review of Environmental Resources, 30*, 221-262.

Newsome, D., Moore, S. A., & Dowling, R. K. (2013). *Natural area tourism: Ecology, impacts, and management.* Channel View Publications.

Noble, B. F., et al. (2007). *The role of community knowledge in ecosystem-based management: A case study in resource management.* Environmental Management, 40(6), 975-986.

Nyong, A., Adesina, F., & Osman, A. (2007). *The role of men in land management and environmental matters in rural and semi-urban communities. Environmental Management,* 39(5), 700–709.

Picard, N., Saint-André, L., & Henry, M. (2012). *Manual for building tree volume and biomass allometric equations: From field measurement to prediction*. FAO & CIRAD.

Pour, M. D., Barati, A. A., Azadi, H., Scheffran, J., & Shirkhani, M. (2023). Analyzing forest residents' perception and knowledge of forest ecosystem services to guide forest management and biodiversity conservation. *Forest Policy and Economics*, *146*, 102866.

Redpath, S. M., Bhatia, S., & Young, J. (2013). *Tackling human-wildlife conflict in a rapidly changing world. Trends in Ecology & Evolution*, 28(9), 515–523.

Reid, R. S., Ellis, J. E., & Young, J. A. (2004). Grazing resources and the livelihoods of pastoral and agro-pastoral communities in arid and semi-arid regions. Global Environmental Change, 14(4), 313–323.

Reed, A., Johnson, L., & Carter, M. (2020). *Human-induced land degradation in drylands: Patterns, processes, and mitigation. Land Use Policy*, 56(4), 87–101.

Robalino, J., et al. (2020). *Community perceptions and economic benefits of protected areas in Latin America: A cross-country analysis of sustainable resource use and tourism.* Environmental Economics and Policy Studies, 22(3), 391-405.

Rocheleau, D. E., et al**.** (1995). *Gender and the environment: A history of the linkages.* Gender, Technology and Development, 1(1), 1-22.

Roe, D ., Elliott, J., & Sandbrook, C. (2013). *Biodiversity conservation and the role of local communities: Insights from protected areas. Conservation Biology*, 27(6), 1293–1301.

Roxburgh, S. H., Paul, K. I., Clifford, D., England, J. R., & Raison, R. J. (2015). *Guidelines for constructing allometric models for the prediction of woody biomass: Examples from Australian ecosystems*. *Agricultural and Forest Meteorology, 210*, 117–132. https://doi.org/10.1016/j.agrformet.2015.03.021

Roxburgh, S. H., Wood, S. W., Mackey, B. G., Woldendorp, G., & Gibbons, P. (2006). Assessing the carbon sequestration potential of managed forests: a case study from temperate Australia. *Journal of Applied Ecology*, *43*(6), 1149-1159.

Roux, D. J., et al. (2020). *Tourism and educational value in South African national parks: Linking well-managed ecosystem services to visitor satisfaction and conservation revenue.* Journal of Environmental Management, 255, 109917.

Santos, M., Araujo, J., & Silva, A. (2022). Ecological services of Vachellia tortilis in protected areas for climate resilience. *Nature Sustainability, 5*(7), 694-702.

Schulze, E.-D., & Houghton, R. A. (2015). Carbon sequestration in protected areas. *Carbon Management*, *6*(4), 243-252.

Sebrala, J., et al. (2022). Destructive sampling techniques for biomass estimation in arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

Shibia, M. I. (2018). *Community perceptions of ecosystem services in Amboseli National Park, Kenya: A study of the relationship between water availability, grazing, and wildlife conflicts.* Journal of Arid Environments, 149, 15-23.

Sileshi, G. W. (2014). A critical review of biomass estimation equations for African tree species. *Forest Ecology and Management, 310*, 1-10. https://doi.org/10.1016/j.foreco.2014.03.001

Siraj, M. (2019). Biomass and carbon stock estimation in arid ecosystems. *Journal of Arid Environments, 45*(3), 211-219.

Smith, L., & Jones, B. (2021). Resilience of *Vachellia tortilis* in arid environments: Implications for climate change mitigation. *Environmental Management, 58*(5), 980-992.

Smit, A., & Prins, H. (2020). Site-specific allometric equations for biomass estimation in semi-arid savannas. *Journal of Arid Environments*, *45*(3), 211-219 .

Smit, H., Janssens, A., & Du, W. (2021). Vachellia tortilis' role in stabilizing soil moisture in arid environments. *Journal of Arid Environments, 189*, 104408.

Sommerville, M., et al. (2016). The role of Vachellia tortilis in carbon sequestration in arid regions. *Journal of Arid Environments, 45*(3), 211-219.

Spertus, J. V. (2021). *Optimal sampling and assay for soil organic carbon estimation*. arXiv. https://doi.org/10.48550/arXiv.2101.07398

TEEB. (2010). *The economics of ecosystems and biodiversity: Ecological and economic foundations*. Pushp Books.

Tengö, M., et al. (2014). *Understanding community perceptions of ecosystem services in relation to local conservation strategies.* Ecology and Society, 19(4), 19.

Thiemann M, Riebl R, Haensel M, Schmitt TM, Steinbauer MJ, Landwehr T, et al. (2022) Perceptions of ecosystem services: Comparing socio-cultural and environmental influences. PLoS ONE 17(10): e0276432.

Thompson, R., Smith, J., & Walker, P. (2019). *Anthropogenic impacts on vegetation in arid regions: Evidence from remote sensing and field studies*. Journal of Environmental Studies, 45(3), 123–138.

Tucker, C. J., & Nicholson, S. E. (2020). *Remote sensing and vegetation dynamics in arid and semi-arid regions: The role of climate and land use changes*. *International Journal of Remote Sensing*, 41(5), 1816–1833.

Turner, R. K., Paavola, J., Cooper, P., Farber, S., Jessamy, V., & Georgiou, S. (2007). *Valuing nature: Lessons learned and future research directions*. *Ecological Economics, 64*(2), 343–352. https://doi.org/10.1016/j.ecolecon.2007.02.005

UNEP-WCMC. (2020). *Protected areas and biodiversity: A global overview of conservation and outreach efforts.* United Nations Environment Programme - World Conservation Monitoring Centre. Retrieved from https://www.unep-wcmc.org/

Wei, F., Wang, S., Fu, B., & Liu, Y. (2020). Representation of biodiversity and ecosystem services in East Africa's protected area network. *Ambio*, *49*(1), 245-257.

Yadeta, T., Veenendaal, E., Sýkora, K., Tessema, Z. K., & Asefa, A. (2018). *Effect of Vachellia tortilis on understory vegetation, herbaceous biomass and soil nutrients along a grazing gradient in a semi-arid African savanna*. *Journal of Forestry Research, 29*(6), 1601–1609. https://doi.org/10.1007/s11676-017-0585-2

Yusuf, S., & Singh, N. (2021). Impact of protected areas on soil carbon stocks: A study of *Vachellia tortilis* in fenced reserves. *Land Use Policy, 102*, 105149.

Zhang, L., & Liu, Y. (2019). *Using remote sensing and vegetation indices to estimate carbon sequestration potential in terrestrial ecosystems. Remote Sensing of Environment*, 231, 111231.

Appendices

Appendix. (1) Questionnaire Survey of the Community

10/10/22, 10:02 PM   Survey on Identification & Assessment of Ecosystem Services in and around As Saleel Natural Park Reserve ... يقة السليل الطبيعية

Survey on Identification & Assessment of Ecosystem Services in and around As Saleel Natural Park Reserve مسح للتعرف ولتقييم خدمات النظم الإيكولوجية داخل وحول محمية حديقة السليل الطبيعية

Any ecosystem provides several benefits to the society and these benefits are known as ecosystem services (ESs). This concept become very prominent these days and it gains wider attention among academics, researchers and policy makers. Moreover, the importance and the value of these services become the basis of decision-making process in conservation of biodiversity. Many studies address the provision services of certain types of ecosystems and their abilities to provides ESs. Only fewer studies addressed the social preferences of ESs. The value to each ecosystem services provided by nature is inferred by how people perceive and use them.

This survey is a part of the research at -the national level - will address the link between people perception and the socio -economic factors and the land use in and around as Saleel nature park reserve .Since this is first study in Oman on ecosystem services and community perception.
On international and regional level, it will address the importance and the role of arid areas in term of benefits it provides to communities in rural areas.

يوفر النظام البيئي العديد من الفوائد للمجتمع وهذه الفوائد تعرف باسم خدمات النظام البيئي. أصبح هذا المفهوم مهمًا وقد جذب اهتمام الأكاديميين والباحثين وأصحاب القرار في جميع أنحاء العالم. علاوة على ذلك ، أصبحت أهمية وقيمة هذه الخدمات أساس عملية صنع القرار في الحفاظ على التنوع البيولوجي. تناول العديد من الدراسات توفير أنواع معينة من النظم البيئية وقدرتها على توفير بيئات بيئية. يتأثر إعطاء القيمة لكل خدمات النظام البيئي التي توفرها الطبيعة في كيفية إدراك الناس لها واستخدامها.

ولذلك ، سيتناول هذا الجزء من البحث على المستوى الوطني العلاقة بين تصور الناس والعوامل الاجتماعية والاقتصادية واستخدام الأراضي داخل وحول محمية حديقة السليل الطبيعية نظرًا لعدم وجود دراسات في عُمان حول خدمات النظام الإيكولوجي وتصور المجتمع عنهم.
على المستويين الدولي والإقليمي ، سيتناول أهمية ودور المناطق القاحلة من حيث الفوائد التي توفرها المجتمعات في المناطق الريفية.

إن تعاونكم في الاجابة على أسئلة الاستبيان يعد بمثابة مساهمة منكم في تقييم خدمات النظم البيئية وكيفية المحافظة عليها مستقبلا لإستدامتها للأجيال القادمة وبالتالي ستكون المخرجات أداة للمساعدة في اتخاذ الاجراءات المناسبة للحفاظ على النظم البيئية في محمية حديقة السليل الطبيعية.

* Required

Part One: General Information , الجزء الأول : معلومات عامة

(Gender الجنس ,Age العمر ,Educational levelالمستوى التعليمي ,Household Income الدخل الأسري, Proximity to the Reserve القرب من المحمية ...etc)

1. Gender الجنس *

Mark only one oval.

- Male رجل
- Female امرأة

2. Age العمر *

Mark only one oval.

- 18-24 yearsمن ثمانية عشر سنة الى اربع و عشرون سنة
- 25-39 years من خمسة و عشرين سنة الى تسعة وثلاثون سنة
- 40-59 years من اربعون سنة الى تسعة وخمسون سنة
- >60 years أكثر من ستون سنة

3. Educational level المستوى التعليمي *

Mark only one oval.

- Primary and under المستوى الإبتدائي ومادونه
- secondary المستوى الاعدادي
- general diploma الدبلوم العام (الثانوية العامة)
- Diploma & Bachelor الدبلوم والبكالوريوس
- Graduate and aboveالدراسات العليا
- Read and Write تقرأ وتكتب
- Not Read nor Write لا تقرأ ولا تكتب

4. Head of household هل أنت المعيل للأسره او ولي الأمر

Mark only one oval.

- Yes نعم
- No لا

5. Household size (Family Members) عدد أفراد الأسره

Mark only one oval.

- one واحد
- 2-4 شخصين الى اربعة اشخاص
- 5-7 خمسة الى سبعة اشخاص
- 8-10 ثمانية الى عشره اشخاص
- >10 أكثر من عشره اشخاص

6. Monthly Income (RO) الدخل الشهري التقريبي *

Mark only one oval.

- <350 RO
- 351-500 RO
- 501-700 RO
- 701-900 RO
- 901-1100 RO
- >1100 RO

7. Duration of residency مده السكن في المكان *

Mark only one oval.

- <6 years اقل من سنوات
- 7-12 years من سبعة سنوات الى اثنا عشر سنة
- 13-18 years ثلاثة عشرة سنة الى ثمانية عشرة سنة
- 19-24 years تسعة عشرة سنة الى اربع وعشرين سنة
- 25years and more خمس وعشرين سنة واكثر

8. Ownership of house *

Mark only one oval.

- Yours ملك
- Rent مستأجر

9. Are you originally from this placeهل أنت من هذا المكان ؟ *

Mark only one oval.

- Yes نعم
- No لا

10. ما اسم القرية التي تسكن فيها ؟ what is the name of the place where you live ? *

Mark only one oval.

- ( ) بسفن
- ( ) الشعيبة
- ( ) طوي داجوري
- ( ) طوي حاتم
- ( ) طوي عائشة
- ( ) سمد
- ( ) سيق
- ( ) سيت
- ( ) طوي حبيب
- ( ) الرق
- ( ) مرخة
- ( ) مركز الولاية

Skip to question 12

Part Two : Preferences of Ecosystem services تفضيل خدمات النظام البيئي

the person must choose 5 ecosystem services and then rank them from 10-5 according to their importance to them 5 اختر فوائد ترى أنها استفدت منها من المحمية ورتبها لاحقا بحسب أهميتها لك والأكثر تفضيلا

11. What are the most five benefits you get from the reserve as ecosystem services? ماهي اهم خمس فوائد تجنيها من المحمية كخدمات النظام البيئي
الرجاء ترتيبها بالأرقام من الأهم الى المهم *

Check all that apply.

- [ ] Fresh Water الماء العذب
- [ ] Timber الحطب
- [ ] Food for Animals المرعى للحيوانات
- [ ] Honey العسل
- [ ] Education & Research التعليم والأبحاث للطلاب
- [ ] Medicinal plants النباتات الطبية والعلاجية
- [ ] Recreational and ecotourism الترفيه والسياحة البيئية
- [ ] Soil regulation فوائد تربة المحمية للمزارع
- [ ] Air purification تنقية الهواء
- [ ] Natural Hazards regulation المساعدة في الحد من الاخطار الطبيعية كالعواصف والاعاصير والفيضانات
- [ ] other please write it أخرى : اذكرها ....

Awareness of protected areas and its importance معرفتك بمصطلح المحميات الطبيعية

determine the awareness and knowledge of the person about protected area in Oman التعرف على معرفتك ودرايتك بالمحميات الطبيعية في عمان واهميتها

12. Are you aware about the meaning of " protected area " by legislation ? هل أنت على دراية محمية طبيعية ماذا تعني *

Mark only one oval.

- ( ) Yes نعم
- ( ) No لا

13. How to do you know for the first time that this is a reserve ? كيف عرفت من المره الاولى عن هذه المحمية *

Mark only one oval.

- from Staff of the Authority موظفي الهيئة
- from any government institutions including schools & colleges المؤسسات الحكومية والمدارس والكليات
- Media الاعلام كالاذاعة والتلفزيون والصحف
- NGOs الجمعيات التطوعية
- Researchers / educators الباحثين والمعلمين
- community members /citizens افراد المجتمع والمواطنين

14. Do you think you have enough information about the reserve ? هل تعتقد أن لديك معلومات كافية عن المحمية ؟ *

Mark only one oval.

- Yes
- No

15. Do you think is important to conserve and protect the habitats inside the reserve ?؟ هل تعتقد بأنه من المهم الحفاظ على الحيوانات والاشجار والتنوع داخل المحمية *

Mark only one oval.

- Yes نعم
- No لا

16. Do you know that the animals and plants is mentioned in Quran to protect them ? هل انت على دراية بأن القرآن الكريم ذكر بأن الإنسان عليه مسؤولية حماية الحيوانات والنباتات الموجوده حوله ؟ *

Mark only one oval.

- Yes نعم
- No لا

Appendix. (2) Dataset coding of the survey responses

Respondent	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15
1	2	2	5	1	2	5	2	1	1	2	2	6	2	1	1
2	1	2	5	1	3	3	2	1	1	1	1	4	2	1	1
3	1	3	5	1	3	6	5	1	1	12	1	6	2	1	1
4	2	3	4	2	3	5	1	1	1	12	1	2	1	1	1
5	1	2	4	1	3	5	1	1	1	12	2	6	2	1	1
6	1	2	3	1	3	2	2	1	1	12	1	6	2	1	1
7	1	3	3	1	4	3	5	1	1	13	1	3	1	1	1
8	1	3	3	1	2	1	1	2	2	12	1	5	2	1	2
9	2	2	4	1	2	5	2	2	1	12	1	6	2	1	1
10	1	2	4	1	4	1	5	1	1	12	1	2	2	1	1
11	2	3	3	2	4	3	4	1	1	13	1	3	1	1	1
12	1	2	3	1	3	2	5	1	1	13	1	1	1	1	1
13	1	2	3	2	4	3	2	2	1	6	1	3	2	1	1
14	1	3	3	1	3	3	5	1	1	2	1	1	1	1	1
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16	1	3	5	1	3	6	2	1	1	4	1	6	1	1	1

17	1	2	4	2	1	1	5	1	1	4	1	2	1	1	1
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19	1	3	4	1	4	6	1	1	1	5	1	2	2	1	1
20	1	3	4	1	3	5	2	1	1	12	1	2	2	1	1
21	1	3	4	1	2	3	1	2	2	13	1	6	2	1	1
22	1	3	4	1	5	6	5	1	1	13	1	2	2	1	1
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24	1	3	5	1	2	6	5	1	1	12	1	2	2	1	1
25	1	3	5	1	2	6	5	1	1	12	1	2	2	1	1
26	1	3	5	1	4	6	2	1	1	12	1	3	2	1	1
27	1	3	4	1	3	6	1	1	1	12	1	6	2	1	1
28	1	2	4	1	2	6	1	1	2	13	1	6	2	1	1
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38	2	3	3	1	2	1	5	2	1	12	1	6	2	1	1
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41	2	2	4	1	3	3	2	1	1	5	1	6	2	1	1
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48	1	2	3	1	3	5	5	1	1	8	1	6	2	1	1
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66	2	2	4	1	4	3	5	2	1	10	1	2	1	1	2
67	1	3	4	1	2	6	5	1	1	13	2	1	2	1	1
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69	2	3	4	1	2	3	3	1	2	4	1	1	2	1	1
70	1	2	2	2	2	2	2	1	2	6	1	1	2	1	1
71	1	1	3	1	2	2	1	1	2	7	1	6	2	1	1
72	1	3	3	1	3	2	4	1	1	4	1	4	2	1	1
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74	2	4	2	2	5	3	1	1	1	2	1	5	2	1	1
75	1	2	4	1	2	3	4	2	2	6	1	6	2	1	2
76	2	1	4	1	3	2	5	1	1	12	1	6	2	2	1
77	1	1	4	1	4	2	5	2	1	7	1	2	2	1	1
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87	2	2	2	2	4	6	5	2	2	12	1	6	1	1	1
88	1	2	5	2	4	6	5	1	2	12	1	6	1	1	1
89	2	1	4	2	3	6	5	2	2	13	1	6	2	1	1

Appendix. (3) Table of fresh-dry weight ratio measurement

Tree Number	Total fresh weight kg	Stems (g)		Branches (g)		Twigs & leaves (g)	
		1st (g)	3rd (g)	1st (g)	5th (g)	1st (g)	6th (g)
2	125 kg	161.6	161	157.1	146.2	150	142.62
6	369 kg	163.5	162.7	193	143.02	150	145.1
7	692 kg	180.8	177.9	180	159.03	200	158.3
8	205 kg	203.5	198.7	177	154	150	135.8
11	120 kg	150.7	149.6	224	165.2	150	126.03
16	575 kg	217.6	216.7	158	151.9	150	145.88
18	120 kg	156.7	155.6	150.7	146.03	200	150.43
19	130 kg	191.5	190.6	168.4	158.03	150	144.02
21	95 kg	176.3	175.9	197.9	145.4	150	155.6
22	227 kg	176	174.6	222	156.03	150	142.35
24	135 kg	153.9	153.27	195.9	139.22	150	142.64
26	350 kg	102.4	101.9	173	155.2	150	143.37
28	50 kg	156.2	154.1	190	133.17	150	119.33
31	330 kg	139.2	138.7	134	132.95	100	119.29
32	200 kg	166.9	166.1	155	152	200	170.92
34	17 kg	148.8	148.1	157.2	124.9	200	144.2
36	870 kg	191.3	190.66	155	148.81	200	162.6
41	195 kg	207.8	206.9	157.2	135.8	200	149.62
43	125 kg	168.2	164.2	213.5	190.55	200	145
45	93 kg	174	173.4	187.8	135.8	150	120.7

Appendix. (4) Summary of Carbon measurements in the study area

PLOT	NUMBER OF TREES	MIN DSH (cm)	MAX DSH (cm)	MIN H (m)	MAX H (m)	MIN CrA (cm)	MAX CrA(cm)
1	9	33	81	2.3	4.4	8	33
2	16	15	80	2	5.6	3.6	38
3	9	17.5	76.4	1.8	4.6	3.1	18.7
4	2	42.6	55.7	2.6	4.2	9.8	10.7
5	8	26.1	76.1	2.6	3.4	4.2	8.9
6	10	5	50.9	2.1	3.8	5	13.5
7	15	21.6	59.2	2	3.4	4.3	13.1
8	4	34.3	102.8	2.7	3.9	5.1	7.8
9	7	28.3	94.5	2.3	3.4	4.2	16
10	8	23.8	154.1	2.6	5	11.8	119.7
11	8	26 .4	60.8	2.5	4.2	7.5	37.8
12	10	17.1	61.1	1.9	3.3	4.6	23.6
13	16	18.1	79.6	1.9	3.7	3.9	41.8
14	25	7.9	62.1	2	4.2	2.1	26.3
15	8	35.6	121	2.2	4.7	10.3	42.9
16	11	5.7	127.3	1.8	6	0.9	38.4
17	16	7	66.5	1.9	4	1.2	19.6
18	6	30.8	67.5	1.8	3.8	1.1	29.2
19	13	19.1	64.3	1.3	3.3	1	12.8
20	11	9.2	98	2	4.7	0.8	26.8
21	11	17.1	71	1.8	5.7	1.2	21.6
22	8	22.2	107.9	2	5.7	1.8	27.3
23	12	23.2	60.8	1.9	4.7	1.5	14.1
24	6	14.3	87.8	2.2	4.6	0.9	13.8
25	13	12.7	47.1	1.8	3.2	3.2	9
26	12	14.3	59.5	1.6	4	2.4	26.8
27	8	17.1	68.4	1.8	3.9	4.7	20.8
28	6	4.7	66.2	1.5	3	1.7	20.4
29	18	11.1	55	1.8	4.5	3.7	23.1
30	8	17.1	45.2	1.4	2.8	4.1	20.4

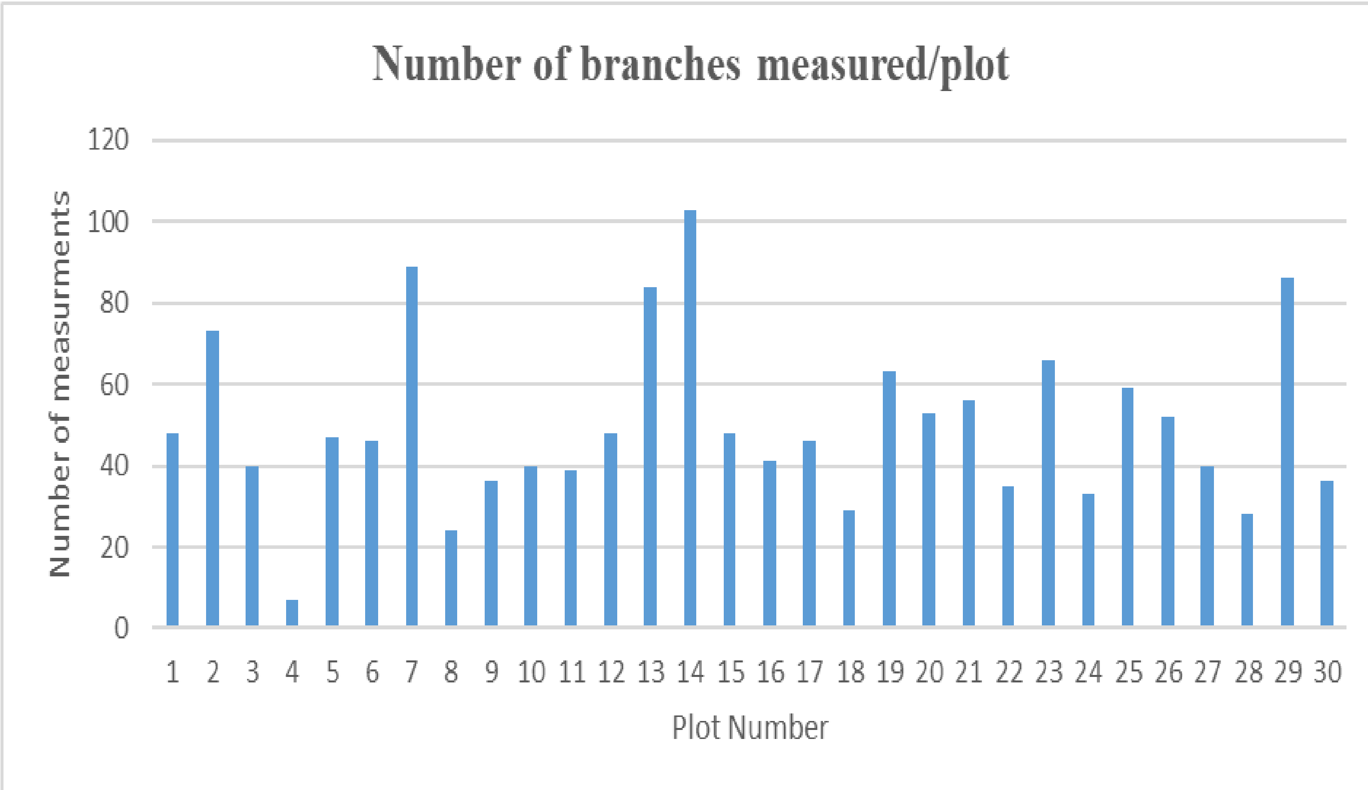
Appendix. (5) Destructive sampling locations in the study area

Plots number	Plot coordinates	Plot location	Elevation	Number of trees /plot
1	E:729978 , N:2474267	East	513 m	6
2	E:729512, N:2474379	East	224 m	6
3	E:728074, N:2474708	middle	216 m	6
4	E:727956, N:2474736	middle	214 m	6
5	E: 726892 , N:2474984	middle	225 m	7
6	E: 726266, N:2475136	middle	238 m	5
7	E:724786, N:2475491	west	231 m	5
8	E:723067, N:2475885	west	251 m	4

Appendix. (6) Table of the 3 transects in the study area

Transect 1 (west)	Transect 2 (Middle)	Transect 3 (East)
30	29	28
25	26	27
24	23	22
19	20	21
18	17	16
13	14	15
12	11	10
7	8	9
6	5	4
1	2	3

Appendix. (7) Numbers of branches measured in 30 plots



Appendix. (8) Classification of *Vachellia tortilis* for destructive sampling based on DSH

	DSH classes	**Number of individuals**	**Number of harvested trees**	**Tree sample numbers**
young	below 40	15	6	11,22,28,34,41,43
pole size	41-63	17	9	6,8,18,19,21,24,31,32,45
standard	above 63	13	5	2,7,16,26,36