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BIOMASS ESTIMATION OF MATURE MANGROVE TREES IN THE UAE USING SPACEBORNE REMOTE SENSING TECHNIQUES

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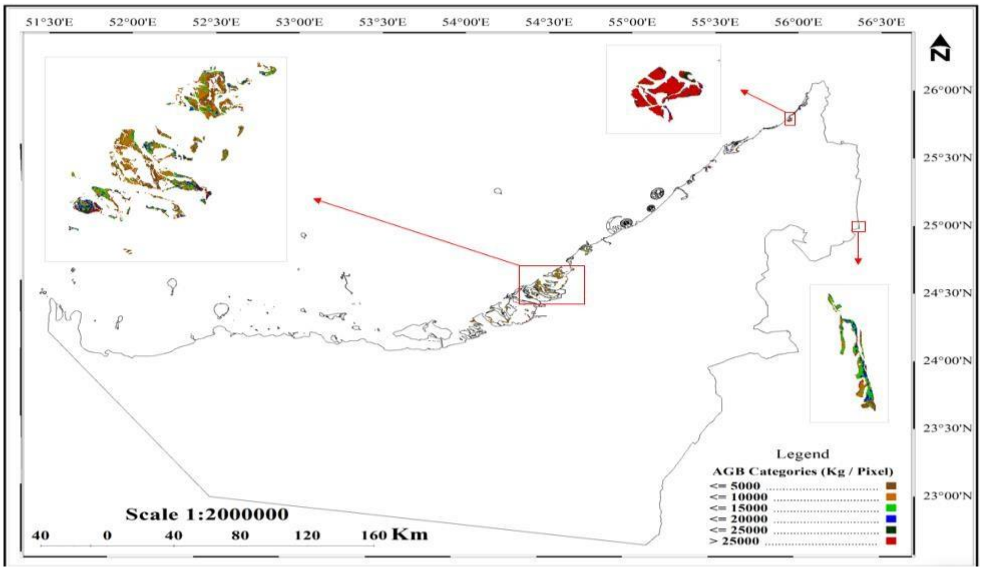

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Space Science

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Cover: Aboveground biomass (AGB) map of mangrove forests in the UAE generated using Landsat-8-9 satellite imagery.

(Photo: By Yasmine Ashraf Said Mohamed Omar Heikal)

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Declaration of Original Work

I, Yasmine Ashraf Said Mohamed Omar Heikal, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Biomass Estimation of Mature Mangrove Trees in the UAE Using Spaceborne Remote Sensing Techniques*", hereby, solemnly declare that this is the original research work done by me under the supervision of Dr. Nazmi Saleous, in the College of Humanities and Social Sciences at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

Mangrove forest ecosystems play an essential role in diminishing the effects of climate change caused by the increase in carbon dioxide in the atmosphere. Estimating mangrove forest aboveground biomass (AGB) and hence aboveground carbon (AGC) can assist in decision-making for conservation, sustainable use, and protection of these forests. The goal of this research project was to map the AGB of mangrove forests along the coasts of the United Arab Emirates (UAE) with the aid of Landsat-8-9 satellite imagery data acquired in September 2023. 12 AGB estimation models were developed based on the combination of in situ measurements and Landsat-8-9 derived vegetation indices. $AGB = 58975\ EVI^{2.7659}$ was the best model selected with $R^2 = 0.8105$ and p-value < 0.005. The average percentage error between the calculated and derived AGB values was 22% which allowed estimation of mangrove forest AGB across the entire UAE. Maps of AGB and AGC were generated and the total values were estimated to be 1,902,653.231 tons and 894,246.882 tons respectively. The results and findings from this study will be used as a standard methodology for environmental studies for the Arab Satellite 813, an Earth-observation satellite to be launched in Q1 of 2025. They could also assist relevant authorities in taking necessary actions.

Keywords: Mangrove Forests, United Arab Emirates (UAE), Aboveground Biomass (AGB) Estimation, Vegetation Indices, Remote Sensing Techniques, Landsat 8 and 9, Carbon Storage.

Title and Abstract (in Arabic)

تقدير الكتلة الحيوية لأشجار المانجروف الناضجة في دولة الإمارات العربية المتحدة باستخدام تقنيات الاستشعار عن بعد المحمولة على متن الفضاء.

الملخص

تلعب النظم البيئية لغابات المانغروف دورًا أساسيًا في تقليل آثار تغير المناخ الناجم عن زيادة ثاني أكسيد الكربون في الغلاف الجوي. يمكن أن يساعد تقدير الكتلة الحيوية لغابات المانغروف الموجودة فوق سطح الأرض (AGB) وبالتالي الكربون فوق الأرض (AGC) في اتخاذ القرارات المتعلقة بحفظ هذه الغابات واستخدامها المستدام وحمايتها. كان الهدف من هذا المشروع البحثي هو رسم خريطة للمساحة الإجمالية الإجمالية لغابات المانغروف على طول سواحل دولة الإمارات العربية المتحدة بمساعدة بيانات صور الأقمار الصناعية Landsat-8-9 التي تم الحصول عليها في سبتمبر 2023. وتم تطوير 12 نموذج لتقدير المساحة الإجمالية للغابات بناءً على مزيج من القياسات في الموقع ومؤشرات الغطاء النباتي المستمدة من Landsat-8-9. كان $AGB=58975\ EVI^{2.7659}$ هو أفضل نموذج تم اختياره باستخدام $R^2 = 0.8105$ والقيمة $p < 0.005$. وكان متوسط نسبة الخطأ بين قيم AGB المحسوبة والمشتقة 22% مما سمح بتقدير غابات المانغروف AGB في جميع أنحاء دولة الإمارات العربية المتحدة. تم إنشاء خرائط AGB وAGC وقدرت القيم الإجمالية بـ 1,902,653.231 طن و894,246.882 طن على التوالي. سيتم استخدام نتائج ومكتشفات هذه الدراسة كمنهجية موحدة للدراسات البيئية للقمر الصناعي العربي 813، وهو قمر صناعي لرصد الأرض سيتم إطلاقه في الربع الأول من عام 2025. كما يمكن أن تساعد السلطات المعنية في اتخاذ الإجراءات اللازمة.

مفاهيم البحث الرئيسية: غابات المانغروف، الإمارات العربية المتحدة، تقدير الكتلة الحيوية فوق الأرض، مؤشرات الغطاء النباتي، تقنيات الاستشعار عن بعد ، لاندسات 8 و9 ,تخزين الكربون.

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Dedication

To my family

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List of Abbreviations

AGB	Above-Ground Biomass
AGC	Above-Ground Carbon
AVHRR	Aerial Very High-Resolution Radiometer
AVIRIS	Aerial Visible / Infra-Red Imaging Spectrometer
CIR	Composite Infra-Red
CO_2	Carbon Dioxide
DBH	Diameter at Breast Height
EAD	Abu Dhabi Environment Agency
EVI	Enhanced Vegetation Index
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
LULC	Land Use / Land Cover
MoCCAE	Ministry of Climate Change and Environment
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multi-Spectral Imager
NDVI	Normalized Difference Vegetation Index
NRIS	Natural Resource Information System
OLI	Operational Land Imager
PAN	Panchromatic
SAR	Synthetic Aperture Radar
SAVI	Soil Adjusted Vegetation Index
SR	Simple Ratio
TIR	Thermal Infra-Red
TIRS	Thermal Infra-Red Sensor

UAE	United Arab Emirates
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VNIR	Visible and Near Infra-Red

Chapter 1: Introduction

1.1 Climate Change and the Global Carbon Cycle

Climate change is an environmental issue that has significant impacts on human and natural ecosystems globally. This phenomenon has resulted in a notable rise in temperature in many regions which increases the number of natural disasters such as droughts, wildfires, and rising sea level [1], [2]. Therefore, global climate change is widely recognized as the biggest challenge facing planet Earth. Most scientists believe that the main cause of this current problem is due to the greenhouse gases effects, carbon dioxide (CO_2) being the most significant one. More importantly, human activities such as the burning of fossil fuels and deforestation has released billions of tons of CO_2 into the atmosphere, resulting in an unbalance of the global carbon cycle [3]. Figure 1 below shows the effects of climate change on human and natural ecosystems [4]. As a result, it is essential to determine and analyze the amount of CO_2 released by human activities and the carbon stored by land and ocean ecosystems. This will aid in better understanding the carbon cycle and hence in designing mitigation policies to reduce emissions. In fact, several studies have suggested that mangrove forests store a relatively large amount of carbon compared to other forests [4] thus implying the significance of mangrove forests in the fight against climate change.

One of the key parameters used in these estimates is aboveground biomass (AGB) which serves as the most critical indicator of carbon sequestration and forest growth [5], [6]. Measuring forest biomass is crucial for understanding and mitigating the effects of climate change. Scientists assess forest biomass and carbon stock estimates using data retrieved from various Earth observation satellites for a variety of vegetation species in different climate zones [7], [8].

Ensuring accurate, timely, and cost-effective estimation of global forest biomass is crucial. However, as of now, there is no worldwide observation program for this purpose. Hence, a quantitative biomass estimation model for each country is required to help design a protocol in order to reduce the negative effects of climate change.

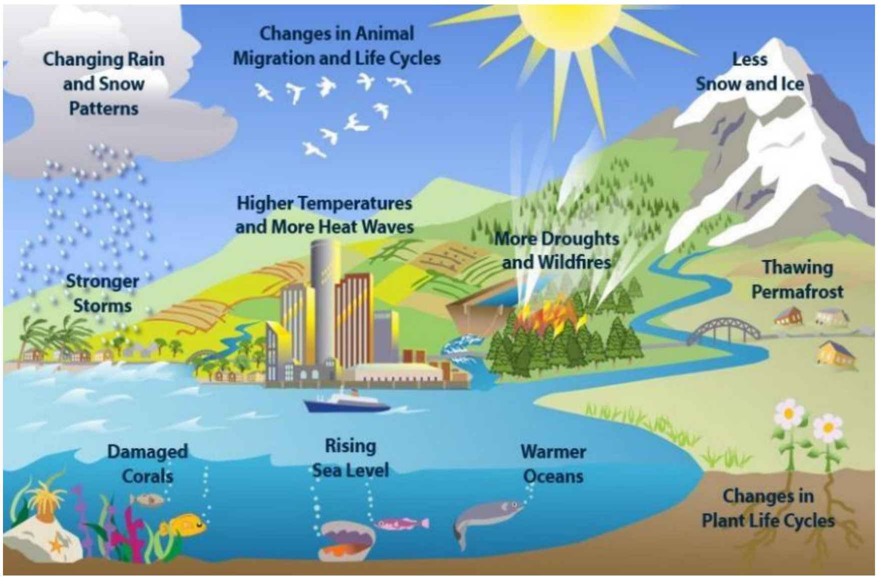


Figure 1: Effects of climate change on human and natural ecosystems.

1.2 Mangrove Forests of the UAE and their Significance

Mangroves are tropical plants that are periodically submerged by tides and can survive harsh conditions. There are approximately 80 different species of mangrove trees around the globe where they grow at tropical and subtropical latitudes near the equator. Climate, salt water, tidal fluctuations, and soil type are four major factors that affect the distribution of those bushy trees [9].

Avicennia Marina is one of the fastest growing and regenerating mangrove species due to its ability to tolerate extreme weather conditions, hyper-saline conditions, and various pests and diseases [10].

Due to the hot arid climate in the region and high saline seawater environment of the UAE, Avicennia Marina is the only type of mangrove species that can survive the harsh environmental conditions and grow naturally in the UAE [11].

Avicennia Marina, sometimes referred to as the Grey Mangrove, is named after the Muslim philosopher Ibn Sina (981 – 1037 C.E.). This is the only mangrove species which abodes well in the Arabian Gulf environment [11]. Nevertheless, historical records show that one other mangrove species, Rhizopohra Mucronata, once grew in the capital - Abu Dhabi [11], [12] . This species has now become extinct due to wood cutting and over-exploitation.

1.2.1 Characteristics of Mangrove Forests

The Grey Mangrove in the United Arab Emirates (UAE) is a unique species with several characteristics. Since they are present near coastal areas (in saltwater), these trees have developed specialized organs and adaptations to be able to survive in high-saline environments. They can filter out salt from the water they absorb or mitigate excess salt through specific glands in their leaves [11]. The average height of mangrove trees found in Abu Dhabi is approximately 4 meters where they do not usually exceed 7 m [11]. Avicennia Marina has short and branchy stems with thick salty leaves and pencil-like roots that grow above the soil surface to a height of about 20 centimeters [11], [12].

Moreover, these mangrove trees are adaptable from their early life stages; they are able to adapt to evolving living conditions as well as reproduce and thrive in aquatic environments. Every mangrove tree in the UAE produces buoyant seeds that can float and travel in water. Avicennia Marina's seeds develop before they detach from the parent plant. Once mature, the healthy seedlings can drop into the water where currents can transport them over long distances and begin their journey to find a suitable and flourishing environment to grow [11].

1.2.2 Ecological and Economic Benefits of Mangrove Ecosystems

Mangrove ecosystems are of particular importance to the United Arab Emirates since they are the only coastal forests that connect land and sea and provide various benefits which are discussed briefly in the sub-sections below.

1.2.2.1 Habitat for Organisms

The mangrove ecosystem serves as a habitat for several marine and terrestrial organisms and maintains a complex aquatic food web. Mangrove trees engage in symbiotic relationships with various organisms including birds, mammals, reptiles, fish, insects, fungi, algae, and seagrass. For instance, sea birds depend on mangroves for their seasonal migrations; they find safe nesting in these vast forests [13]. In fact, mangrove forests in Abu Dhabi host up to 300,000 sea birds during the main migratory season [11].

1.2.2.2 Pollution Control

Another significance of mangrove forests belonging to the UAE is that they are able to control pollution in air and water. They can serve as filters that separate sediments and nutrients in polluted areas along the coast which therefore maintains water quality and hence ensures the health of coral reefs across the emirates [10]. They also act as natural barriers against ocean waves along the shoreline of the UAE; they protect the coastline against erosion and destruction caused by strong waves, ocean currents, and winds [12]. Mangrove forests are widely known for reducing the amount of carbon emission in coastal areas by the process of carbon sequestration [12]. As mentioned above, these ecosystems act as a sink for CO_2 by storing excess carbon as biomass; the more biomass a mangrove tree has, the greater the amount of carbon stored.

1.2.2.3 Lumber and Energy Source

Besides aiding to control pollution, mangroves once supplied forestry products like timber, firewood, and charcoal due to their high calorific values. Historically, mangrove trees were used to produce quality timber for construction in the UAE. The wood was used for building homes and ships due to its hardness and high resistance to rot and termites. They also provide energy, acting as fuel in the form of firewood and charcoal. However, after the discovery of oil, mangrove trees are no longer used as a source of energy or lumber in the UAE [14].

Mangroves undoubtedly play an essential role in the environment. These ecosystems support diverse marine organisms, provide a habitat for various species, and protect coastal communities from erosion and storm surges. Mangrove forests are valuable reservoirs of carbon which are able to store enormous amounts of CO_2 from the atmosphere [4]. These ecosystems are vital since they contribute significantly to the attempts to reduce the effects of climate change [15]. For this reason, there are strategies in place by various authorities and agencies of the UAE to safeguard and increase the number of mangrove trees along its coastlines. Furthermore, accurate and continuous monitoring as well as measurement of biomass and carbon concentration are necessary in order to conserve and manage mangrove forests [16].

1.2.3 Threats to Mangrove Forests

Since the population in the United Arab Emirates significantly increased over the past couple of years, so did negative human activities. Many mangrove trees have been lost due to urbanization and industrialization across the region [17], [18]. These projects, along with the rising population, affect mangrove forests by altering the hydrological cycle which is essential for aquatic habitats and their ecosystems. Moreover, oil spills coming from oil extraction, exploitation, and transport pose a major anthropogenic threat to the mangrove forests in the UAE. However, as long as the aerial roots of Avicennia Marina are not fully contaminated, the mangrove species survives [11].

Along with human activities there exists several natural threats such as climate change both of which contribute to the decline of mangrove distribution and density across the region [18]. As a consequence of global warming, the mean sea level has risen which poses a significant threat to mangrove forests and their coastal ecosystems worldwide [19]. These trees then cannot move inland due to coastal development and human settlement. Studies conducted by Abu Dhabi Environmental Agency revealed that the effects of increasing sea level could eradicate mangrove forests across the region by 2100 [11].

Temperature is one of the main factors that influence mangrove forest distribution. Mangrove trees are able to thrive in areas where the average temperature is $25°C$ [10], [12]. However, due to anthropogenic activities, the Earth's temperature has been increasing globally which in turn deteriorates the state of mangrove forests [18]. The Arabian Gulf region is likely to experience an increase in the intensity and frequency of hot and dry weather conditions. This severe state combined with the effects of climate change, such as a decrease in precipitation, will negatively affect the mangrove ecosystem in the UAE by minimizing their survival rates [11].

1.2.4 Mangrove Protection

Mangrove ecosystems are vital to many countries around the world including the United Arab Emirates. These trees control pollution by filtering out waste, absorbing excess water during floods, protecting land from storm effects, and play an essential role in decreasing carbon emissions which contribute to mitigating the effects of climate change [20]. However, mangrove forests have been lost and destroyed due to anthropogenic and natural causes. Therefore, several governmental bodies, agencies, and private organizations in the UAE have collaborated to maintain and enhance these forests by increasing public awareness, enforcing regulations and laws, establishing protected areas, and increasing mangrove plantations [12].

One of the most common methods of protecting mangrove ecosystems is the establishment of marine protected areas across the emirates. These protected natural reserves aid in the conservation of valuable species which can then be reproduced in captive breeding. Moreover, since fishing activities are prohibited inside the reserves, aquatic animals are now at no risk and can increase in quantity [11]. A proven significant approach used to increase the amount of mangrove trees in the UAE is by establishing mangrove plantations. Mangrove plantations can be noticed across the emirates since they were established in the late 1970s. However, survival and growth are below expectations due to the harsh climate of the UAE along with insufficient knowledge on plantations [11]. A total of 6,600 saplings were planted in Al Zorah Nature Reserve Forest in Ajman in November 2023 which is equivalent to 2 hectares. More research and development programs were initiated by Abu Dhabi Environment Agency (EAD) to improve plantation techniques for Avicennia Marina and enhance the possibilities of reviving the extinct Rhizopohra Mucronata. Therefore, to conclude, estimating aboveground mangrove biomass can assist authorities in decision-making for conservation, sustainable use, and protection of mangrove forests.

1.3 Project Value

The research and information concluded from this project will be valuable for similar environmental studies of the Arab Satellite 813 which is an Earth-observation satellite carrying a hyperspectral sensor. It will be placed in a low-Earth sun-synchronous orbit and is expected to launch in the first quarter (Q1) of 2025. In addition, the generated results can be used as a reference for 2023 for future studies and satellite missions in the same region. It can also be utilized by relevant authorities to take any necessary actions.

1.4 Project Objectives

The main purpose of this present work is to employ advanced remote sensing techniques by utilizing digital satellite imagery data from existing multispectral sensors as well as ground-based measurements in order to estimate biomass and to assess carbon sequestered in mangrove trees across the United Arab Emirates.

The research objectives are:

- Develop knowledge base and the standard methodology for estimating biomass and carbon sequestered in mangrove trees.
- Determine efficient remote sensing predictors for estimating aboveground biomass (AGB) of mangrove forests and develop various regressions in order to find the best estimation model.
- Estimate aboveground biomass and carbon present in mangrove forests across the entire UAE and individual emirates while utilizing satellite imagery and remote sensing techniques to portray the distribution of mangrove forests across the region.

1.5 Research Questions

The primary research questions we aim to address in this work are:

1. What are the important parameters / variables needed to be considered when using remote sensing techniques for estimating carbon sequestered in mangrove forests?
2. What is the impact of remote sensing data spatial resolution on the accuracy of mangrove biomass and carbon estimates?
3. What is the total amount of mangrove biomass present across the UAE?
4. What is the total amount of carbon stored in mangrove trees in the UAE?

Chapter 2: Literature Review

2.1 Biomass Estimation Using Remotely Sensed Data

Biomass is defined as the total mass of all living organisms such as plants, trees, crops, and other vegetation classifications, as well as organic matter in the soil per unit area [21]. The units of biomass differ depending on the field or discipline of study. For instance, kilogram / hectare (kg / ha) where 1ha = 10,000 m^2 and tons / hectare (tons / ha*)* are commonly used in applications of forestry and agriculture [21].

Estimating biomass is an essential parameter in ecological and environmental studies which provides critical information on the health of the ecosystem, resource management, and carbon storage [22]. Accurate estimation of forest biomass is essential for the latter in order to quantify carbon stocks and track any changes in carbon storage to better understand the global carbon cycle and its effects on climate change [23]. Knowledge of the amount of biomass in a particular forest would aid relevant authorities into taking necessary actions.

Remote sensing data, such as satellite imagery and aerial photography, provide methods to estimate biomass over different spatial and temporal scales [24]. Remote sensing assists scientists to estimate aboveground vegetation biomass (AGB) and provides valuable information for carbon stock assessments. This is due to the ability to capture spatial information and constant monitoring in remote and inaccessible areas. Numerous researchers developed methods to estimate AGB based on the relationship between biophysical parameters of forests such as diameter at breast height (DBH), basal area, crown cover, and the response value of the electromagnetic radiation [4]. Optical, Synthetic Aperture Radar (SAR), hyperspectral, and Light Detection and Ranging (LiDAR) techniques have been used for accurately estimating AGB for tropical forests as well as mangroves [7], [21], [25], [26].

2.1.1 Biomass Estimation Using Optically Sensed Data

Remotely sensed data can be used to estimate AGB with different approaches including multiple regression model, machine learning, and neural network [23].

Aboveground biomass could be estimated based on different spatial resolutions of optical sensors; high, medium, and coarse.

High spatial resolution sensors, such as QuickBird, can be used to estimate forest biomass [4]. The spatial resolution of their panchromatic images are 0.83 m and 0.61 m respectively. The high-resolution satellite imagery extracted from these sensors can be used as reference information in order to validate or assess the accuracy of medium or low-resolution data [4]. For instance, a linear regression was utilized based on the three main textural indices and yielded accurate predictions of total aboveground mangrove biomass. An empirical regression model was developed to estimate wet and dry biomass of oil palm plantations in Africa using IKONOS images based on field plot data [27]. However, there are several challenges of using high spatial resolution data; the complexities of forest canopy and topography may cause difficulty when building models or equations for estimating AGB. Also, purchasing high-resolution imagery can be quite expensive and will therefore require more time and expertise to analyze [4].

Optical sensors with spatial resolutions ranging from 10 to 100 meters are termed medium resolution sensors. The time-series Landsat data are commonly used in various applications including biomass estimation [23]. There are numerous methods developed to estimate forest AGB using medium spatial resolution data. Most approaches depend on identifying remote sensing predictors that can be used to estimate AGB using empirical models [28].

Shadows resulting from canopy as well as topography may lead to uncertainties or errors in estimations of biomass [29]. To improve the accuracy of AGB estimation using Landsat data, six empirical models were developed by using NDVI (Normalized Difference Vegetation Index) time-series. The results showed that using the time-series of NDVI provides a more accurate estimation and less saturation than using a single one [26]. Multiple other vegetation indices have been utilized to remove variability caused by environmental conditions and other factors.

Landsat-8 satellite imagery, which has a 30 m spatial resolution, offers a new primary data source for aboveground biomass estimation [4]. Texture parameters derived from Landsat-8 data provide an important tool for updating AGB maps which in turn provide greater accuracy in biomass estimation [30]. A scientist pointed out that Landsat-8 can produce more precise results than Landsat-7 ETM+ when estimating vegetation biomass. This is mainly associated with the higher signal-to-noise ratio performance and higher radiometric resolution of Landsat-8 [31].

In the field of remote sensing, optical sensors that provide a spatial resolution >100 m are often called low or coarse resolution sensors. AVHRR and MODIS are examples of passive spaceborne sensors that offer coarse resolution satellite imagery data [1 km and 250 m respectively] which can be utilized at national, continental, and global scales [4], [32]. AVHRR NDVI can be implemented to estimate biomass density and atmospheric emissions in Africa as well as assess forest biomass in six European nations. A combination of multi-scales data is sometimes applied to estimate AGB. For instance, a combination of AVHRR and Landsat TM data was used to estimate biomass of coniferous forest [33].

Hyperspectral images can provide high spectral resolution by utilizing a large number of narrow spectral bands ranging from visible to shortwave infra-red (SWIR) [34]. The Airborne Visible / Infrared Imaging Spectrometer (AVIRIS) is one example of a unique hyperspectral sensor with 224 contiguous spectral bands and a wide wavelength range of 380 nm – 2510 nm [34]. It is mentioned that these sensors have the potential to be the best in estimating vegetation biomass compared to other multispectral sensors [4]. In fact, hyperspectral data can provide relatively higher accuracies in estimating grass biomass than the Sentinel-2 multispectral imager (MSI) data [35]. However, it was stated that the sole use of hyperspectral data had limited prediction ability in estimating forest biomass with a coefficient of determination $R^2 = 0.36$ [35]. Various studies have shown that the integration or merging of LiDAR and hyperspectral or multi-source data can remarkably improve the accuracy of aboveground biomass estimates [36], [37].

2.1.2 Other Assessment Methods

Advances in remote sensing technologies, particularly SAR (Synthetic Aperture Radar) and LiDAR (Light Detection and Ranging), have significantly enhanced the ability to estimate forest biomass accurately and efficiently.

SAR is an active remote sensing technique that uses microwave signals to create high-resolution images of the surface of the Earth. These systems operate in different frequency bands (X, C, L, and P-bands) and polarizations (HH, HV, VH, VV) [34]. Unlike optical sensors, SAR can penetrate cloud cover and operate during the day and night in all weather conditions which poses as an advantage [4], [38]. Nevertheless, SAR image processing requires more expertise and scientific knowledge. In addition to the expensive cost, SAR data is captured in limited areas where AGB estimation in regional and global scales has not been used extensively due to the constraints of cost and labor [4].

Short wavelengths could interact with the surface of the canopy while longer wavelengths such as L-band (15 – 30 cm) and P-band (68 cm) could easily penetrate into the canopy and reflect valuable information on branches and stems. Studies have shown that longer wavelengths could provide a relationship between biomass and other biophysical parameters [39], [40]. Furthermore, the use of different polarizations can help gather diverse knowledge on the target which improves the differentiation of various vegetation types and structures. The HV polarization along with L- and P-bands have proven to be the most sensitive to AGB estimation [4], [40].

The most common method for biomass estimation is by using regression analysis based on a backscattering coefficient value extracted from SAR data and field survey biomass measurement [41]. Another approach is interferometry which is based on the interference of waves leading to one with greater or lower amplitude which provides more accurate results [4].

Another approach that is significantly used for biomass estimates is LiDAR. LiDAR is an active airborne, spaceborne, or terrestrial sensor that uses a pulsed laser to measure ranges, examine the surface of the Earth, and create detailed three-dimensional (3D) maps of terrain and vegetation [34]. This technology has the potential to present a 3D structure of forests, offering advantages for measuring various vegetation attributes over high-resolution satellite imagery [5]. However, it does have limited spectral information due to one wavelength of laser point intensity. LiDAR data has crucial roles in estimating AGB since their pulses can penetrate certain vegetation canopy especially in the tropics where frequent cloud conditions occur [4].

Recent studies have shown the potential of merging between LiDAR and SAR data to map height and biomass of mangrove forests [42]. The different types of information from both technologies provide a complete picture of forest biomass and health. It should be noted that direct biomass estimation methods using airborne LiDAR can offer higher accuracy in AGB estimation than those from radar and optical data [43] since LiDAR can characterize both horizontal and vertical canopy structure [44]. However, LiDAR data is still considered limited as it is only captured in small areas and is more costly than data obtained from spaceborne for a larger area [4]. Pham [4] stated that a combination between SAR and optical data would be the potential choice due to the reasonable cost and time of data processing while an integration of optical, SAR, and LiDAR would be the best choice for estimating AGB.

2.2 Basic Method of Biomass Estimation of Mangrove Forests

The basic method of aboveground mangrove biomass estimation involves measuring or evaluating the total amount of living or organic material present in a particular mangrove forest. This estimate is crucial to understanding and assessing the carbon concentration of mangroves globally and is beneficial for monitoring changes in mangrove ecosystems [4]. There are various methods used to estimate biomass which depend on the type and species of vegetation studied, the remote sensor used, and the primary mission objectives [24]. With the aid of a few techniques, optical remote sensing data can be used to estimate AGB. In fact, vegetation indices are a commonly used technique in many studies [25], [35].

Prior to the use of remote sensing data, in-situ field measurements must be carried out. This method involves collecting samples from different plot locations and weighing in all the wet and dry aboveground mangrove biomass including leaves and stems. This technique can be time consuming, difficult, expensive, and can involve destructive procedures that can harm mangrove trees as well as the environment. However, this gravimetric approach is one of the most accurate methods of producing an allometric equation for a particular area [21]. Alternatively, current methods of biomass estimation rely on a combination of remote sensing techniques along with field work that causes no damage to the ecosystem. Structural parameters such as DBH, tree height, etc. can be directly measured and remote sensing predictors can be used to formulate empirical models [8], [12], [16], [31], [41].

Optical remote sensing data from previous missions or existing satellite archives is required [21], [24]. Based on the preferred spatial and spectral resolutions of the mission requirements, digital imagery from multispectral (Landsat) or hyperspectral sensors (Hyperion) can be used. To ensure that the imagery data acquired is ready for further analysis, image preprocessing - to enhance the quality and accuracy of the data - may be needed to correct for atmospheric effects, geometric distortions, and radiometric calibration [32]. Next, vegetation indices are calculated based on the surface spectral reflectance values and equations over a specified area [21]. These indicators capture the vegetation’s greenness and can act as proxies for biomass [25]. In other words, the greener (healthier) the vegetation, the more carbon is absorbed rather than released into the atmosphere and hence a larger value of biomass is measured. Ground-based biomass measurements within the desired study area must also be collected and compared with inventory data while ensuring that the data covers a wide range of biomass values. Biomass estimation models are then developed based on experimental relationships between ground-based measurements and the corresponding vegetation indices calculated.

Statistical criteria are calculated to evaluate the accuracy and performance of the model produced [21]. Then, the model is applied to the entirety of the dataset to estimate biomass. The vegetation indices previously calculated are utilized as input to estimate the biomass content. The predicted output values are used to create biomass distribution maps which provide beneficial information on the spatial patterns and variations of biomass over large areas. These maps can also be used to assess changes or compare measurements [16].

The above-mentioned method has a few challenges and recent advances. Estimating biomass accurately or monitoring of any rapid changes can be difficult since optical remote sensing data often have limited spatial and temporal resolutions [21].

Another drawback is that not all vegetation is homogeneous: this can lead to inaccurate biomass estimations especially in mixed land cover types [4]. The recent development of high-resolution optical sensors has improved the spatial resolution of imagery data. A latest trend includes the fusion of data from optical and radio remote sensors (as well as ground-based field work) to improve the accuracy and reliability of the estimates [36].

Current methods of biomass estimation based on literature rely on field measurements. This can be time consuming, costly, and difficult to maneuver, especially in dense mangrove forests. Hence, this results in inadequate information on the structure and biomass of mangrove trees. Moreover, the development of accurate models to estimate the biomass of mangrove species is necessary to support mangrove management and conservation programs [4]. This is extremely beneficial for the United Arab Emirates with a goal to plant 100 million mangrove trees across the country by the year 2030 [45].

Satellite remote sensing data has been globally utilized for monitoring mangrove forests [4], [15], [16]. Biomass estimation of mangrove forests in the UAE can be considered limited. This is due to the fact that existing studies are restricted to specific regions or emirates [12], [14].

The objective of this research study is to build an understanding of Avicennia Marina and to develop an accurate AGB estimation model based on vegetation indices that can be utilized to estimate biomass and carbon content of mangrove trees across all emirates in the UAE. Landsat-8-9 satellite imagery as well as remote sensing techniques will be utilized along with the non-destructive method. Field work will consist of measurements taken that cause no harm to the mangrove trees. Furthermore, since the Arab Satellite 813 will be used for environmental studies including estimating forest biomass, the methodology built throughout this research can be beneficial or advantageous.

Chapter 3: Study Area and Data Used

This chapter introduces the United Arab Emirates as the designated study area and briefly lists the chosen satellite data used for this research project.

3.1 The Study Site

The United Arab Emirates is located in the Southeast of the Arabian Peninsula and borders the two countries of Saudi Arabia and Oman. In 1971 the UAE became a federation of seven emirates: Abu Dhabi, Dubai, Sharjah, Ajman, Umm Al Quwain, Ras Al Khaimah, and Fujairah with Abu Dhabi being the capital city. The UAE held the COP28 international climate summit in Dubai in 2023 in order to focus on climate change impacts and solutions [46].

The geographic coordinates of the study area as shown in Figure 2 are between 22°50' and 26°N latitude and 51° and 56°25'E longitude with a total area of approximately 83,600 km^2 [9], [47]. The terrain of the UAE is mostly flat barren coastal plains and sand dunes of vast desert (which causes frequent sand and dust storms) with mountains in the Northeastern emirates. Energy resources include petroleum and natural gas.

In Abu Dhabi, the major ecosystems consist of the coastal and interdunal sabkha, numerous islands, mountainous areas, gravel plains, and the sand desert. About 100 km inland, dunes rising to 200 meters are present [9]. Mountains are commonly found in the Northern Emirates with the highest altitude reaching around 1934 m (Jebel Jais in Ras Al Khaimah – a mountain of the Northwestern Hajar range).

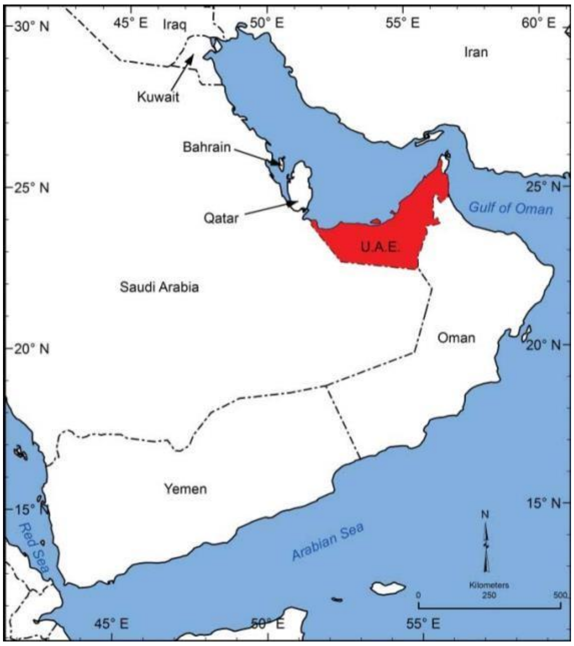


Figure 2: Location map of the UAE.

3.1.1 *Climate*

The region generally experiences little to no rainfall with extremely high humidity. The UAE experiences an arid climate characterized by severe and dry summers with temperatures often surpassing 45℃, alongside mild to warm winters. The United Arab Emirates has a typical desert climate with hot and dry conditions. The weather during the winter months is pleasant with a maximum temperature of 26℃ whereas the summer months are unbearable with temperatures ranging from 33℃ to 50℃ along the coast and higher in the interior desert. A significant decrease in temperature is observed on top of mountains situated in the northern emirates whereas coastal areas experience high humidity.

There is little to no rainfall across the study area – the average annual rainfall is <100 mm with an average of 25 rain days per year. However, these numbers can increase due to cloud seeding. During the year, the study site may be affected by strong winds which could cause sand and dust storms throughout the region.

3.1.2 Topography

The UAE is mostly a barren land with extensive sand deserts, yet it is also characterized by oases, mountains, valleys, mangroves, and salt plains (sabkhas). The study area has an average elevation of 85 m and two coastlines. The longer coast (>700 km) faces in a northwestern direction into the Arabian Gulf while the shorter coast (~70 km) faces eastwards into the Gulf of Oman. Most of the Arabian Gulf coastline is flat and bordered by shallow water whereas the shorter coastline is eroding with a large number of hard rocks. This had led to a variety of marine organisms.

3.1.3 Mangrove Forests of the UAE

Although the study area is too dry or barren to support vegetation, mangrove forests can be found along the coast across most emirates. There are approximately 156km^2 of mangrove trees within the UAE, 75% of which are found across the capital [48]. Mangroves are able to survive in harsh environments (such as high temperatures) and are the only evergreen forest in the UAE. Traditionally, the only species of mangrove forest currently present in the UAE is the Avicennia Marina commonly known as the Grey Mangrove. These mangrove trees serve as a home to many marine organisms such as Greater Flamingo, Western Reef Heron, Kalba Collared Kingfisher, etc. and therefore form a fundamental part of the marine ecosystem [9].

Khor Kalba in Sharjah contains the oldest mangrove forest in the UAE (~300 years) [49] whereas the largest mangrove forest by area across the study site can be found in Mangrove National Park in Abu Dhabi (>19 km^2) [47]. Moreover, the UAE's Ministry of Climate Change and Environment (MoCCAE) is aiming to plant 100 million mangrove trees by 2030 across the country in accordance with the 'National Carbon Sequestration Project' [45]. Figure 3 below shows two mangrove forests visited during the in-situ measurements.

Figure 3: Images obtained from two mangrove forests within the UAE.

3.2 Data Used

The datasets utilized in this study include freely available Landsat ETM+ satellite imagery as well as a field campaign performed across the study area. The details of the data collected and employed are discussed below and in Chapter 4 - Methodology.

3.2.1 Satellite Data

Remote sensing data is obtained from multispectral satellite imagery with suitable spatial and spectral resolutions along with necessary metadata such as sensor information, acquisition date, and satellite-specific parameters. Landsats-8 and -9 are utilized for the scope of this project. Landsat 8 is an Earth-observation satellite jointly owned by NASA and the United States Geological Survey (USGS) which is part of the long-running Landsat program. It was launched in February 2013 with a main purpose to image and analyze the surface of the Earth for various applications including land use / land cover monitoring, disaster management, and environmental studies. It is placed in a low-Earth polar Sun-synchronous orbit (with an altitude of 705 km and an inclination of 98.2°). It has an orbital period of 99 minutes and a repeat cycle of 16 days. Landsat-9 was launched in September 2021 with the same objectives and applications mentioned above. In addition, it has the same orbital parameters as Landsat-8 [50].

There are two scientific instruments onboard each satellite that constitute the payload: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These two sensors provide seasonal coverage at a spatial resolution of 30 meters (VNIR), 100 meters (TIR), and 15 meters (panchromatic PAN). Details of the spectral bands of each payload are shown in Table 1 [50].

Table 1: Spectral bands of the two instruments onboard Landsat-8-9.

Band Name	**Band Number**	**Wavelength Range (μm)**	**Spatial Resolution (m)**
Coastal Aerosol	Band 1	0.43 - 0.45	30
Blue	Band 2	0.450 - 0.51	30
Green	Band 3	0.53 - 0.59	30
Red	Band 4	0.64 - 0.67	30
Near Infra-red	Band 5	0.85 - 0.88	30
SWIR 1	Band 6	1.57 - 1.65	30
SWIR 2	Band 7	2.11 - 2.29	30
Panchromatic PAN	Band 8	0.50 - 0.68	15
Cirrus	Band 9	1.36 - 1.38	30
TIRS 1	Band 10	10.6 - 11.19	100
TIRS 2	Band 11	11.5 - 12.51	100

This project offers a baseline for the Arab Satellite 813 which utilizes an optical hyperspectral sensor to observe the surface of the Earth. Therefore, we will analyze Landsat-8-9 satellite digital imagery within bands 2 – 6 (VNIR).

High resolution multispectral satellite imagery from Landsat-8-9 were downloaded from the USGS Earth Explorer website and analyzed on Catalyst Earth software. Table 2 shows the scenes collected across the UAE. This digital imagery data is used to portray the extent and distribution of mangrove trees in the UAE. This data can also be beneficial for calculating various vegetation indices such as Normalized Difference Vegetation Index (NDVI) to assess the health and vitality of mangrove forests. Once data analysis of satellite imagery is completed, it can be used to help estimate the amount of biomass stored in mangrove forests across the UAE and hence the carbon content.

Table 2: Scenes collected and utilized across the study area.

Landsat Type	**Path**	**Row**	**Acquisition Date (2023)**
LC09	162	043	September 6
LC08	161	043	September 7
LC08	161	044	September 7
LC09	160	042	September 8
LC09	160	043	September 8
LC09	160	044	September 8
LC08	159	042	September 9
LC08	159	043	September 9
LC08	162	043	September 14
LC09	161	043	September 15
LC09	161	044	September 15
LC09	160	043	September 16
LC09	160	044	September 16
LC09	161	043	September 22

3.2.2 Field Campaign

Ground-based measurements are collected from the field across the study area where mangrove forests are present. Extensive field work was carried out in three locations in the UAE to measure various parameters including mangrove tree height, diameter at breast height (DBH), and GPS coordinates which would help in estimating aboveground biomass using several regressions. Field data was collected using tape measure, meter stick, etc. with the help of a mirrorless digital camera (SONY lens FE 28-70 mm F3.5-5.6 OSS Lens) and a PhotoMeasure software which made the process of data collection easier since not all areas were easily accessible.

The camera lens used in this project has a focal length range of 28-70 mm. Although the lens does not have a constant aperture, it is still capable of producing good results in various lighting conditions. The lens also features Optical SteadyShot image stabilization which helps in reducing the effects of camera shake. Moreover, the lens is constructed with multiple aspherical and dispersion elements to minimize aberrations and distortions. This contributes to producing sharp and high-resolution images.

The structural parameters measured on the field include mangrove tree height, DBH, number of trunks per mangrove tree, and the approximate number of trees available in 25 m^2 plot size. Other parameters were derived or calculated such as basal area and AGB. Figure 4 shows images taken from the field.

Figure 4: Collecting tree attributes in Mangrove National Park and Khor Kalba.

Chapter 4: Methodology

4.1 Methodology

Estimating biomass and carbon stock of mature mangrove trees within the UAE using multispectral satellite data involves several steps and methodologies. Figure 5 below represents a general flowchart to achieve this objective. The steps involved in this research project are discussed in the sub-sections below.

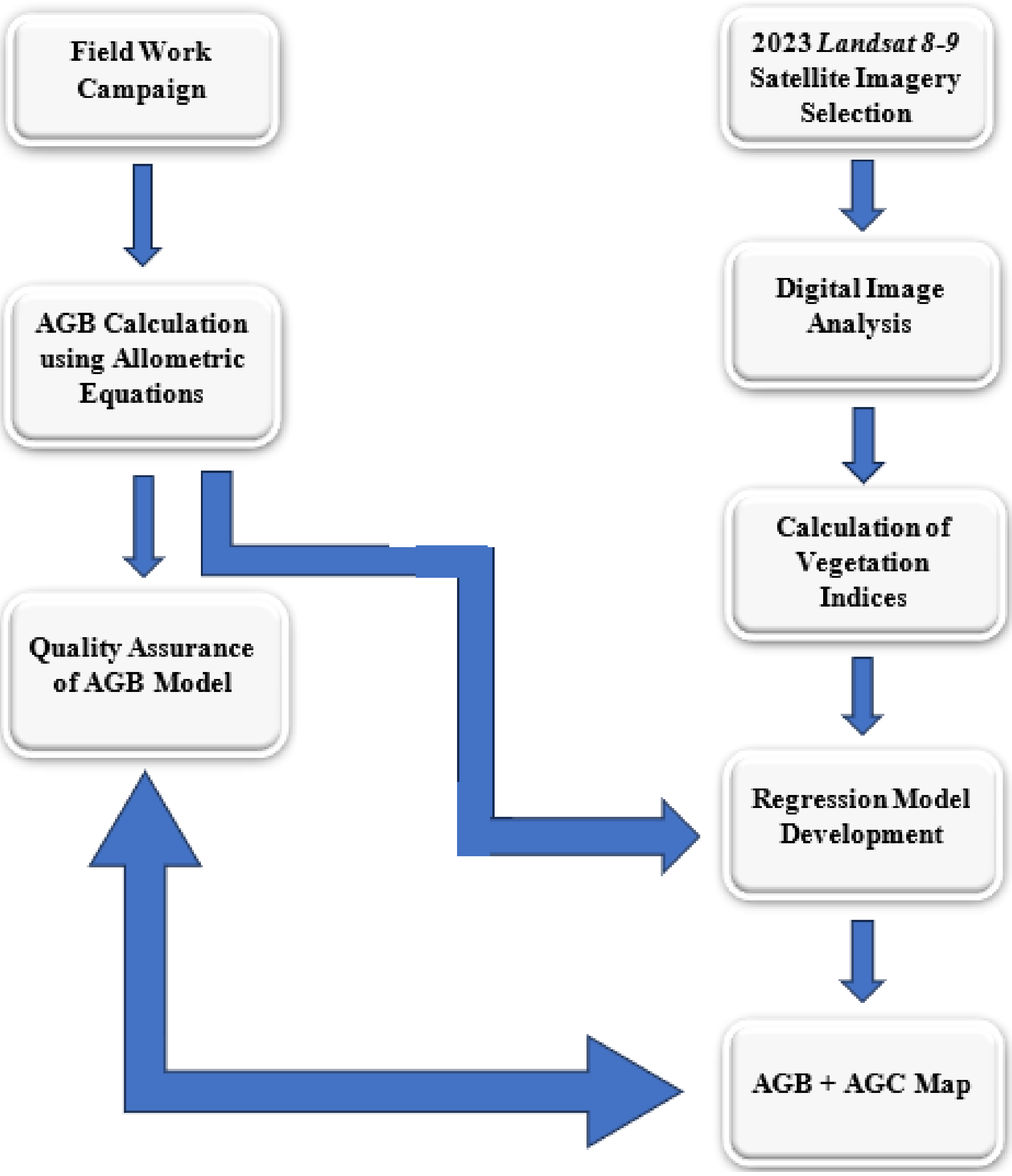


Figure 5: Steps involved in estimating aboveground biomass using spaceborne remote sensing techniques and a field campaign.

4.2 Field Work Campaign

Ground-based measurements are needed to verify the results based on the analysis. Extensive field work was completed at three mangrove forest locations in the UAE in order to measure required parameters.

The Natural Resource Information System (NRIS) recommends having one sampling plot per 4 hectares. However, 3 – 4 plots were established in each of the 3 locations due to various factors: working in mangrove swamps poses challenges due to the presence of mud and large root-like mangrove structures as well as the fluctuation of tidal waters; a significant portion of the study area comprises dense forest that is difficult to maneuver through to collect tree attributes; and high temperatures during the summer restrict the collection of parameters to the winter season due to safety concerns [12].

The sample plots surveyed covered a wide spectrum of forest structural variability within the study area. To ensure representation of diverse conditions, plot locations were randomly distributed.

4.2.1 Tree Attributes

Tree parameters were obtained from direct measurements at the ground plot level which were then used to calculate further measurements. Table 3 below includes a description of each parameter [12].

Table 3: Definitions of tree attributes directly measured from each sampling plot.

Direct Tree Parameters	Definition
Trunk Number	The total number of trees in a plot
Tree Height	Distance between the top and the base of a tree measured using a meter stick
Diameter at Breast Height (DBH)	Trunk diameter of a tree usually measured at 1.3 m above ground

Derived measurements are calculated as follows [12]:

- Absolute (tree) density is the number of mangrove trees per hectare such that $1 \text{ hectare} = 10{,}000 \text{ m}^2$. Tree density was calculated using:

$$\text{tree density} = \frac{\text{\# of trees}}{\text{area of plot (m}^2\text{)}} \times 10{,}000 \text{ m}^2 \quad (1)$$

- Basal area is the area of Earth occupied by tree trunks and stems (measured in m^2) [12].

$$\text{BA (m}^2\text{)} = 0.00007854 \times \text{DBH}^2 \quad (2)$$

- Mean plot height is simply the average height of the mangrove trees at each of the 3 locations.
- Aboveground biomass (AGB) is the amount of vegetation matter per unit area. It is calculated as the dry mass of tree elements above ground [12]. Aboveground biomass was obtained from DBH ground measurements using the following allometric equation:

$$\text{M} = \text{aD}^{\text{b}} \quad (3)$$

M is the total aboveground dry biomass (kg), D corresponds to DBH measured in cm, and a and b are constants estimated to be 0.5317 and 1.7476 respectively [12], [16]. However, a better estimation of AGB can only be obtained by measuring the oven-dry mass of different trees of all sizes in the study area and then allometric equations can be developed for accurate AGB estimation.

- Aboveground carbon (AGC) was calculated by multiplying AGB by a conversion ratio of 0.47 [16].

$$\text{AGC} = 0.47 \times \text{AGB} \quad (4)$$

4.2.2 Materials and Methods

The field work was conducted in December 2023 in three locations across the UAE to ensure cooler weather conditions with the help of the United Arab Emirates University, the National Space Science and Technology Center, as well as permission from local authorities. Any measurements collected did not cause any damage or harm to the mangrove ecosystem. The three locations chosen for this particular field work are Eastern Mangrove Lagoon National Park in Abu Dhabi, Al Zorah Mangrove Park in Ajman, and Khor Kalba Mangrove Center in Sharjah. Figure 6 displays the location map of each study site marked in black squares. All mangrove forests are of the same species – Avicennia Marina. Samples are not allowed to be collected since the visited mangrove forests are protected nature reserves. Three sample plot locations were chosen at random in Abu Dhabi and Ajman while four plots were chosen in Sharjah.

Figure 6: The locations of the three visited mangrove forest sites in the UAE.

Tree attributes mentioned in Table 3 above are measured directly at each sample plot. The latitude and longitude coordinates of each plot were determined using a GPS receiver and recorded. The two tree parameters that are of most importance in this project are tree height (TH) and Diameter at Breast Height (DBH). Tree height is defined as the distance between the top and the base of a tree which is measured using a height stick. DBH is the trunk diameter of a tree measured at 1.3 m above the ground using a measuring tape. If it is not possible to record this measurement due to the limited access to the mangrove trees and restrictions, which is the case in a few plots, pictures were taken at each sample plot location that is later used for PhotoMeasure.

An important factor to note is that the measurement obtained using a measuring tape around the tree trunk is the circumference. Therefore, simple calculations are required to obtain the diameter:

$$C = 2\pi r \rightarrow 2r = D = \frac{C}{\pi} \tag{5}$$

where C is the circumference, r is the radius, and D is the diameter of the trunk. We then need to insert the image into PhotoMeasure software and obtain multiple diameters at 1.3 m for multiple trunks and take the average. This average value will be taken as DBH.

After obtaining necessary structural parameters, aboveground biomass was calculated using the allometric equation mentioned above [Equation (3)] for each sample plot location. Various graphs were plotted such as DBH vs. TH, BA vs. DBH, TH vs. BA, TH vs. AGB, and BA vs. AGB to check for any correlation using the coefficient of determination (R^2) measure. Lastly, aboveground carbon (AGC) was calculated using Equation (4) for each sample plot.

4.3 Digital Satellite Imagery Analysis

Landsat-8-9 OLI imagery data are readily available at no cost on the USGS Earth Explorer website. The United Arab Emirates is selected as our study area by placing pinpoints around the desired location or by including longitude and latitude coordinates. The dates selected for this study are between September 1 and September 22, 2023. The scenes that intersect our study area and have little to no cloud cover obscuring are downloaded. Landsat-8-9 imagery data is readily available in a geometrically and radiometrically corrected format known as Level-2 data (surface reflectance) which is ready to use with no pre-processing needed [50]. Table 2 shows the chosen scenes.

4.3.1 Stack + Mosaic

Surface reflectance bands, bands 2 – 6 shown in Table 1 above, are utilized for the scope of this project. Stacking Landsat bands enhances the interpretation of the data, facilitates various types of analysis, and provides valuable insights into the surface of the Earth and its changes over time [32]. On those grounds, bands 2 – 6 are stacked on top of each other in each scene downloaded and are numbered bands 1 – 5 in the stack. The results are multiple individual stacked images of each scene collected.

Image mosaicking is a process in remote sensing and digital image processing that involves combining multiple individual scenes to create a seamless and larger image of a larger area [32], [34]. This step is performed on Catalyst Earth software to obtain a complete image of the UAE. Since our focus in this project is on mangrove forests, a composite infra-red image (CIR) will be best for analysis utilizing RGB bands as Bands 4-3-2 (NIR-Red-Green). This is simply used for visualization purposes to easily locate vegetation areas since vegetation has a high surface reflectance in the NIR Band.

4.3.2 Image Classification

Image classification is a fundamental task in remote sensing that is widely used for satellite image analysis. It involves the process of categorizing each pixel or object within a digital image into clusters or classes based on their spectral characteristics. The goal of image classification is to assign a class to the different land cover types in the image to be able to easily distinguish our region of interest [16], [32], [34].

Unsupervised image classification was performed on the mosaicked image of the UAE. All 5 stacked surface reflectance bands are selected as input, and one 8-bit channel is added as an output layer. The k-means unsupervised classification algorithm was applied for this study with the system default k-value to produce 20 clusters in order to obtain better separation of image pixels [32]. The generated classes were then manually compared based on prior knowledge of the study area, the CIR image, as well as using other resources such as Google Earth Pro in order to accurately merge them into five main classes, namely water, open areas [bare land, sand, dried channels, etc.], vegetation, mangroves, and urban infrastructure.

Accuracy assessment on the classified image was performed using Catalyst Earth software to evaluate the reliability of the classification results and to ensure that the different image pixels are assigned to accurate and correct classes [16]. A total of twenty-one testing samples for the five land covers were chosen using stratified random selection in order to generate the confusion matrix. This is considered limited and can lead to unreliable estimates; however, ensuring that each class is represented as evenly as possible can help in mitigate some of the bias and variance issues.

Overall accuracy along with kappa coefficient (κ) are derived from the generated error matrix. $\kappa > 0.6$ can be considered as a good agreement and a land use / land cover map can be produced [32].

4.3.3 Vegetation Indices

Vegetation indices that are relevant to mangrove health assessment are calculated using the 'Raster Calculator' tool on Catalyst Earth, an image processing software. These indicators provide necessary information on the density and health of vegetation. Most importantly, they are used to develop multiple regression models in order to estimate aboveground biomass [16].

Table 4: Equations of vegetation indices used for the AGB estimation model.

Vegetation Index	**Equation**	**Remarks**
Simple Ratio SR	$\mathrm{SR} = \frac{\rho\mathrm{NIR}}{\rho\mathrm{Red}}$	
Normalized Difference Vegetation Index NDVI	$\mathrm{NDVI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \rho\mathrm{Red}}$	
Soil Adjusted Vegetation Index SAVI	$\mathrm{SAVI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \rho\mathrm{Red} + \mathrm{L}} \times (1 + \mathrm{L})$	L is the soil adjustment factor typically set to 0.5
Enhanced Vegetation Index EVI	$\mathrm{EVI} = \mathrm{G} \times \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \mathrm{C1} \times \rho\mathrm{Red} - \mathrm{C2} \times \rho\mathrm{Blue} + \mathrm{L}}$	G = 2.5, L = 1, C1 = 6, C2 = 7.5

Four vegetation indices mentioned in Table 4 [32] were derived from Landsat-8-9 at the different sample plot locations based on the latitude / longitude coordinates collected which were then utilized to plot AGB versus each individual index using several regressions models including linear, exponential, and power trendlines to obtain the best regression model. The model with the highest R^2 value and a P-value < 0.005 will be selected and used in the 'Raster Calculator' to estimate AGB for all mangrove forests across the UAE. Carbon content stored is calculated using Equation (4) and subsequently, AGB and AGC maps are generated displaying different categories of biomass and carbon values in order to establish an understanding of the amount of biomass and carbon stored in mangrove forests across the UAE as well as in individual emirates.

Chapter 5: Results and Discussion

5.1 Characteristics of Avicennia Marina at Eastern Mangrove Lagoon National Park - Abu Dhabi

The characteristics of mangrove trees in Abu Dhabi sites are summarized in Table 5 that displays the measurements obtained from three sample plot locations in the field.

Table 5: Different mangrove structural parameters measured in Abu Dhabi.

Sample Plot	**Tree Height (m)**	**DBH (cm)**	**# of Trees in 5×5 m Plot Size**	**Coordinates**
1.	3.2	9.215	14	137° SE 24°27′5"N 54°26'24"E
2.	2.45	12.45	16	180°S 24°27′5"N 54°26'23"E
3.	2.75	11.60	13	90°E 24°27′5"N 54°26'24"E

The mangrove tree heights in Abu Dhabi are relatively low compared to other mangrove forests in the region where the majority of trees are less than four meters. Therefore, direct tree attributes were measured for Tree Height > 1.3 m. This low height allows seedlings to colonize the area as there is more sunlight and space available for them to grow [12]. Moreover, diameter at breast height (DBH) and the age of a mangrove tree are related; the older the mangrove tree is, the larger the diameter at 1.3 m above the ground.

Aboveground biomass is estimated using the diameter at breast height at each sample plot location by applying allometric Equation (3). AGB was calculated in kilograms for each individual mangrove tree, then in kilograms per 25 m^2 using the tree density above, and lastly converted to tons per hectare using a simple conversion factor [1 ton = 1000 kg and 1 hectare = 10,000 m^2]. The results are summarized in Table 6.

Table 6: Derived measurements calculated using values obtained from the field in Abu Dhabi.

Sample Plot	Basal Area (m^2)	AGB (kg / 1 tree)	AGB (kg/ 25 m^2)	AGB (tons/ hectare)
1.	0.00667	25.776	360.864	144.346
2.	0.0122	43.61	697.76	279.104
3.	0.01057	38.54	501.02	200.408

To convert the AGB of mangrove forests into aboveground carbon (AGC), a conversion ratio of 0.47 was applied as in Equation (4). AGC was calculated to be 67.842, 131.179, and 94.192 tons per hectare respectively.

The in-situ field work data shows that this particular mangrove forest in Abu Dhabi is generally healthy with a low mortality rate. There is a relatively high population of young trees and saplings in this study site, which is ordinary for a naturally regenerating forest. The increasing number of young trees could be a result of the UAE's vision to plant 100 million mangrove trees by 2030.

5.2 Characteristics of Avicennia Marina at Al Zorah Nature Reserve – Ajman

The characteristics of mangrove trees in Ajman sites are summarized in Table 7 that displays the measurements obtained from three sample plot locations.

Table 7: Different mangrove structural parameters measured in Ajman.

Sample Plot	Tree Height (m)	DBH (cm)	Coordinates
1.	3.4	4.138	170°S 25°26′7"N 55°28'44"E
2.	7.0	12.97	154°SE 25°26′4"N 55°28'44"E
3.	4.5	19.42	34°NE 25°26′4"N 55°28'45"E

Al Zorah mangrove forest is extremely dense and therefore due to accessibility issues, we were not able to obtain the number of trees in 25 m^2 area from the field. There are approximately 500,000 mangrove trees in 1 million m^2 in this particular forest in Ajman [45]. Consequently, using simple computation $\left[\frac{500{,}000 \text{ trees} \times 25 \text{ m}^2}{10^6 \text{ m}^2}\right]$, there are around 12 mangrove trees in 25 m^2 area; this value can be used as Tree Density for further calculations.

Basal area and AGB for Ajman mangrove sites are calculated using Equations (2) – (3) and are summarized in Table 8.

Table 8: Derived measurements calculated using values obtained from the field in Ajman.

Sample Plot	**Basal Area (m^2)**	**AGB (kg / 1 tree)**	**AGB (kg/ 25m^2)**	**AGB (tons/ hectare)**
1.	0.001345	6.362	76.34	30.536
2.	0.013212	46.843	562.11	224.84
3.	0.02962	94.844	1138.13	455.25

Aboveground carbon (AGC) was estimated to be 14.352, 105.68, and 213.97 tons per hectare for each sample plot respectively.

Sample 1 in Al Zorah has a very low DBH value compared to other mangrove trees because it was located on the outskirts of the forest; perhaps it was newly planted. This measured value will affect other derived measurements as in Table 8. On that account, we do expect some uncertainties and error from this measurement while developing the AGB estimation model.

5.3 Characteristics of Avicennia Marina at Khor Kalba Mangrove Center – Sharjah

The characteristics of mangrove trees in Khor Kalba sites are summarized in Table 9 that displays the measurements collected from four sample plot locations.

Table 9: Different mangrove structural parameters measured in Khor Kalba.

Sample Plot	Tree Height (m)	DBH (cm)	Coordinates
1.	7.68	32.37	28° NE 25°0′57"N 56°21'37"E
2.	4.8	12.6	0°N 25°0′37"N 56°21'50"E
3.	4.55	12.2	80°E 25°0′37"N 56°21'51"E
4.	5.0	34	209°SW 25°0′57"N 56°21'37"E

Khor Kalba is the oldest mangrove forest in the UAE – around 300 years old [45]. Since DBH and the age of a mangrove tree are directly proportional, a larger diameter at 1.3 m above the ground for older mangrove trees is expected. This can be clearly shown in Khor Kalba where DBH reaches 34 cm according to our sample measurements above. This mangrove forest is extremely dense containing huge trees both in diameter and height. Due to inaccessibility, tree density was obtained from 'Abu Dhabi Global Environment Data Initiative' which stated that there are around 3,613 trees per hectare [51] or approximately 9 mangrove trees per 25 m^2 area. This is the lowest tree density found in the three mangrove forests visited but was comprised of large mature trees.

Basal area and AGB for Khor Kalba mangrove sites are calculated using Equations (2) – (3) and are summarized in Table 10.

Table 10: Derived measurements calculated using values obtained from the field in Khor Kalba.

Sample Plot	**Basal Area (m^2)**	**AGB (kg / 1 tree)**	**AGB (kg/ 25 m^2)**	**AGB (tons/ hectare)**
1.	0.0823	231.63	2084.67	833.87
2.	0.01247	44.532	400.79	160.32
3.	0.01169	42.091	378.819	151.53
4.	0.0908	252.39	2271.51	908.6

Aboveground carbon was estimated to be 391.92, 75.35, 71.22, and 427.042 tons per hectare respectively. Khor Kalba has a great amount of biomass and carbon stored due to the fact that the older the mangrove tree is, the more can be stored.

5.4 Summary of the Characteristics of Avicennia Marina at all Three Locations

This section summarizes all parameters measured and calculated at the three mangrove forest locations visited in the UAE (Tables 11 – 12). Additionally, five regression plots are displayed in Figure 7 to study the relationship between various parameters of mangrove trees. Coefficients of determination (R^2) are utilized to display a correlation table below (Table 13).

Table 11: Summary of AGB and AGC values in tons per hectare for all sample plots at the three site locations visited in the UAE.

Location	**Sample Plot**	**AGB (tons / hectare)**	**AGC (tons / hectare)**
Abu Dhabi	1.	144.3456	67.842
Abu Dhabi	2.	279.104	131.179
Abu Dhabi	3.	200.408	94.192
Ajman	1.	30.536	14.352
Ajman	2.	224.846	105.678
Ajman	3.	455.2512	213.968
Sharjah	1.	833.87	391.92
Sharjah	2.	160.32	75.35
Sharjah	3.	151.53	71.22
Sharjah	4.	908.6	427.042

Table 12: Summary of all important values of structural and derived parameters.

Location	Sample Plot	Tree Height (m)	DBH (cm)	Basal Area (m^2)
Abu Dhabi	1.	3.2	9.215	0.00667
Abu Dhabi	2.	2.45	12.45	0.0122
Abu Dhabi	3.	2.75	11.60	0.01057
Ajman	1.	3.4	4.138	0.001345
Ajman	2.	7.0	12.97	0.013212
Ajman	3.	4.5	19.42	0.02962
Sharjah	1.	7.68	32.37	0.0823
Sharjah	2.	4.8	12.6	0.01247
Sharjah	3.	4.55	12.2	0.01169
Sharjah	4.	5.0	34	0.0908

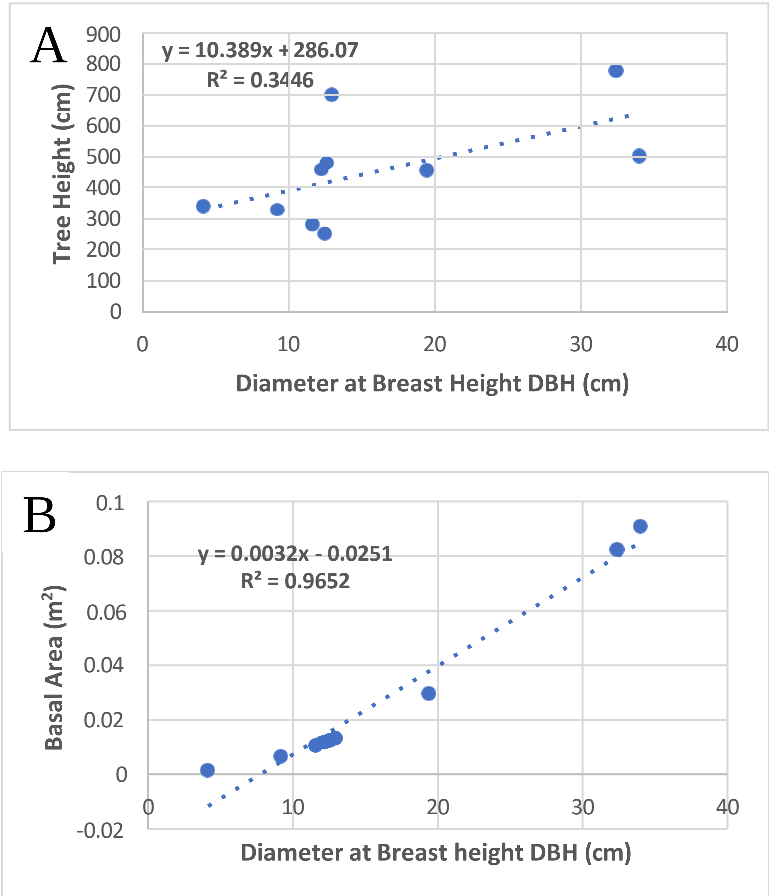


Figure 7: Relationships between DBH, basal area, tree height, and aboveground biomass of Avicennia Marina.

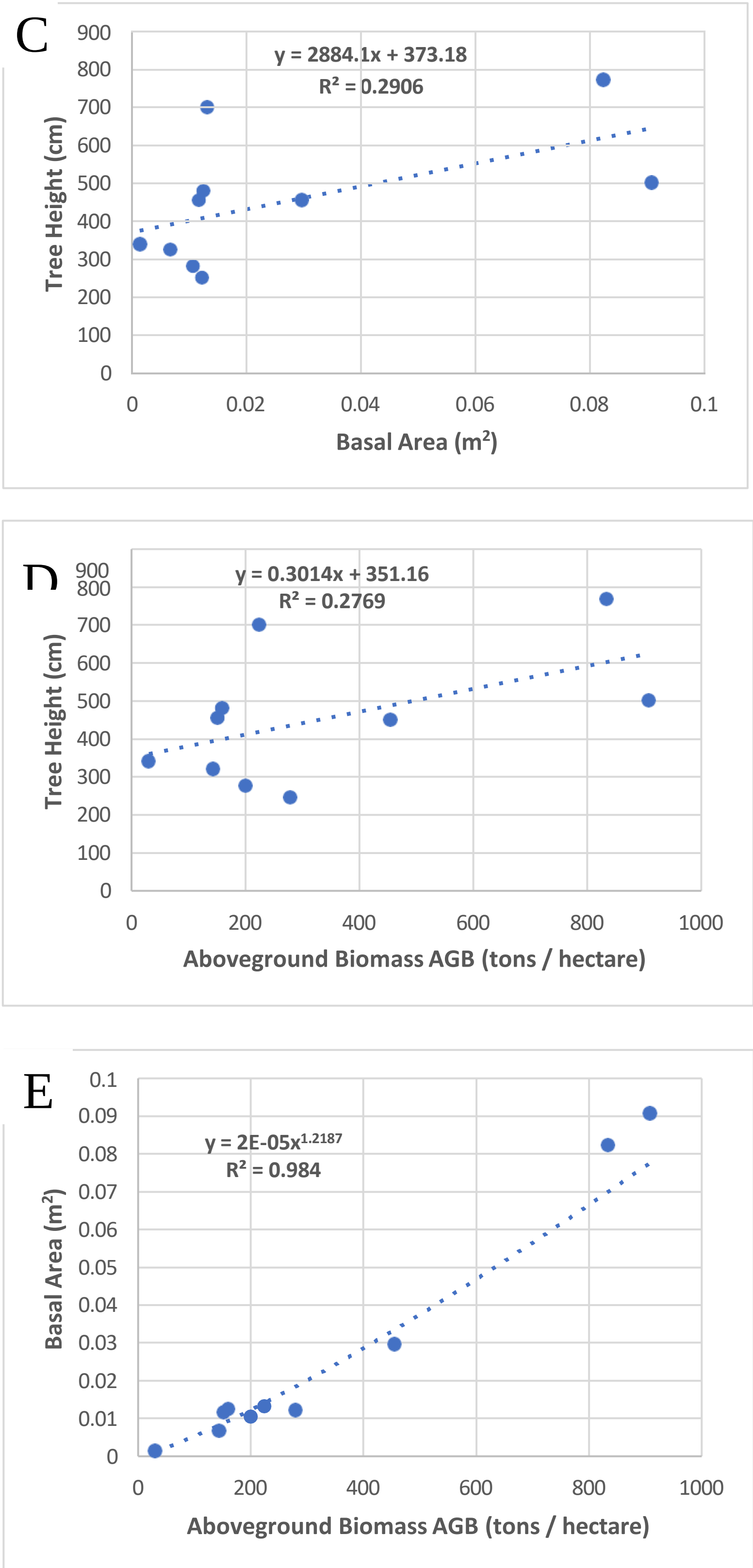


Figure 7: Relationships between DBH, basal area, tree height, and aboveground biomass of Avicennia Marina (Continued).

Table 13: Correlation coefficient (r) among mangrove structural parameters and aboveground biomass.

Parameters	**Tree Height**	**DBH**	**Basal Area**	**AGB**
Tree Height	1.000	0.587	0.539	0.503
DBH	0.587	1.000	0.982	N/A
Basal Area	0.539	0.982	1.000	0.992
AGB	0.503	N/A	0.992	1.000

Figure 7 (E) is displayed using a power trendline since aboveground biomass is calculated with a power allometric equation. All other regressions are performed with a linear trendline.

Based on the correlation table between the various parameters above, basal area is the most correlated with AGB with a correlation coefficient of 0.992. Tree height is the least correlated parameter with AGB ($r = 0.503$). As a matter of fact, height has the weakest correlation with all parameters.

When a mangrove tree grows over a period of time, its DBH increases along with its biomass; likewise, height and basal area increase as well. Therefore, we expect a high correlation coefficient between TH vs. DBH and Basal Area vs. DBH. However, tree height is the least correlated between all parameters.

Some difficulties we experienced in the field were: Abu Dhabi was muddy and difficult to go through, however we managed to obtain all necessary measurements and photos. Ajman and Kalba were extremely dense mangrove forests and natural reserves, therefore we were only able to enter through a walkway and collect our measurements and as many photographs to aid us. One of the uncertainties faced would definitely be human error while using the measurement tape, height stick, and PhotoMeasure software. Therefore, our measurements collected from the fieldwork above may not be completely accurate but should be adequate for estimations. The lack of field work data points is expected to harm the experiment; however, due to weather conditions, time constraints, and accessibility issues, these were all the data points that we were able to collect.

5.5 Satellite Imagery Data Analysis Using Remote Sensing Techniques

The following sections show and discuss the results obtained while implementing remote sensing techniques on Catalyst Earth software in order to analyze field data more efficiently and to generate an AGB estimation model.

5.5.1 Stacking and Mosaicking

Figure 8 below was obtained by stacking bands 2 – 6 of each individual scene collected (Table 2) from Landsat-8-9 and mosaicking them together to create one seamless image of our study area. A zoomed-in image of a portion of the capital – Abu Dhabi – is shown.

The RGB bands chosen for this project are NIR, Red, and Green which make up a composite infra-red (CIR) image that aids in visualization. This type of composite image can assist us in clearly differentiating between various land cover types.

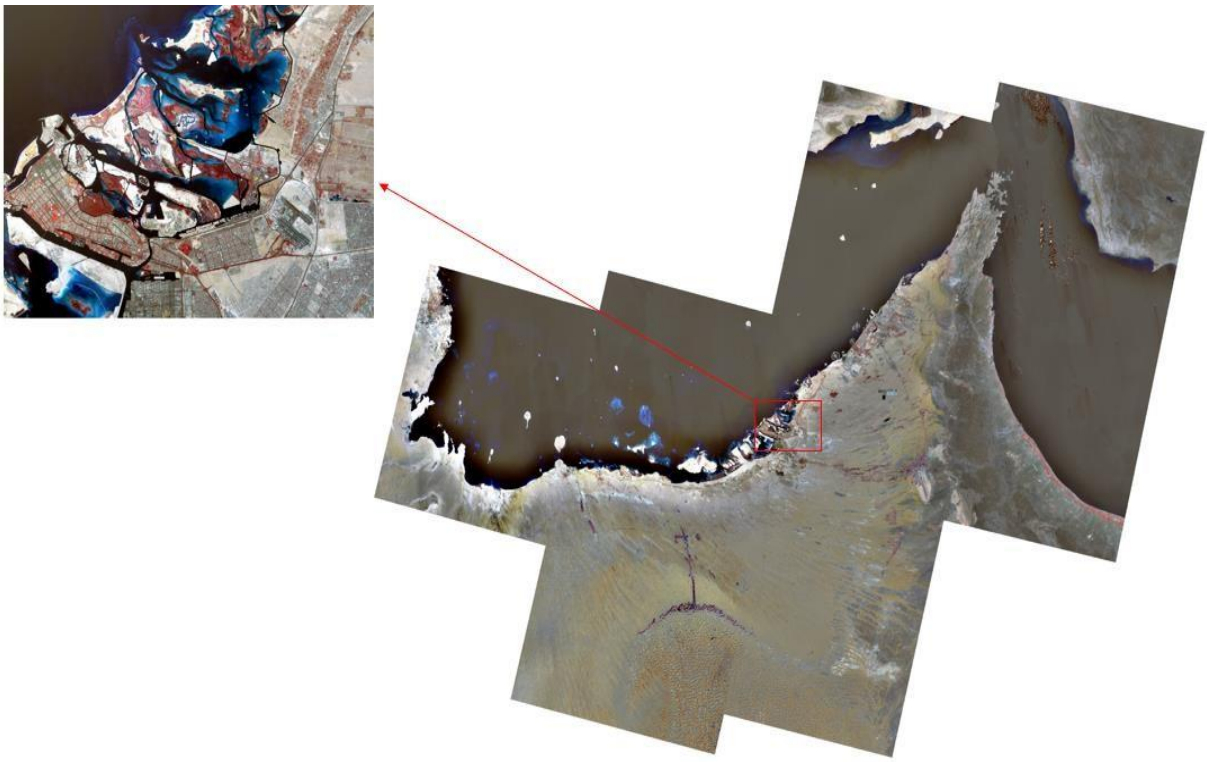


Figure 8: Complete mosaicked image of the UAE.

5.5.2 Image Classification and Extraction of Mangrove Forests Across the UAE

This study focuses on the mangrove forests present across the United Arab Emirates. The land use / land cover (LULC) map and the extent of mangrove forests within the UAE are shown as results below in Figures 9 and 11 respectively.

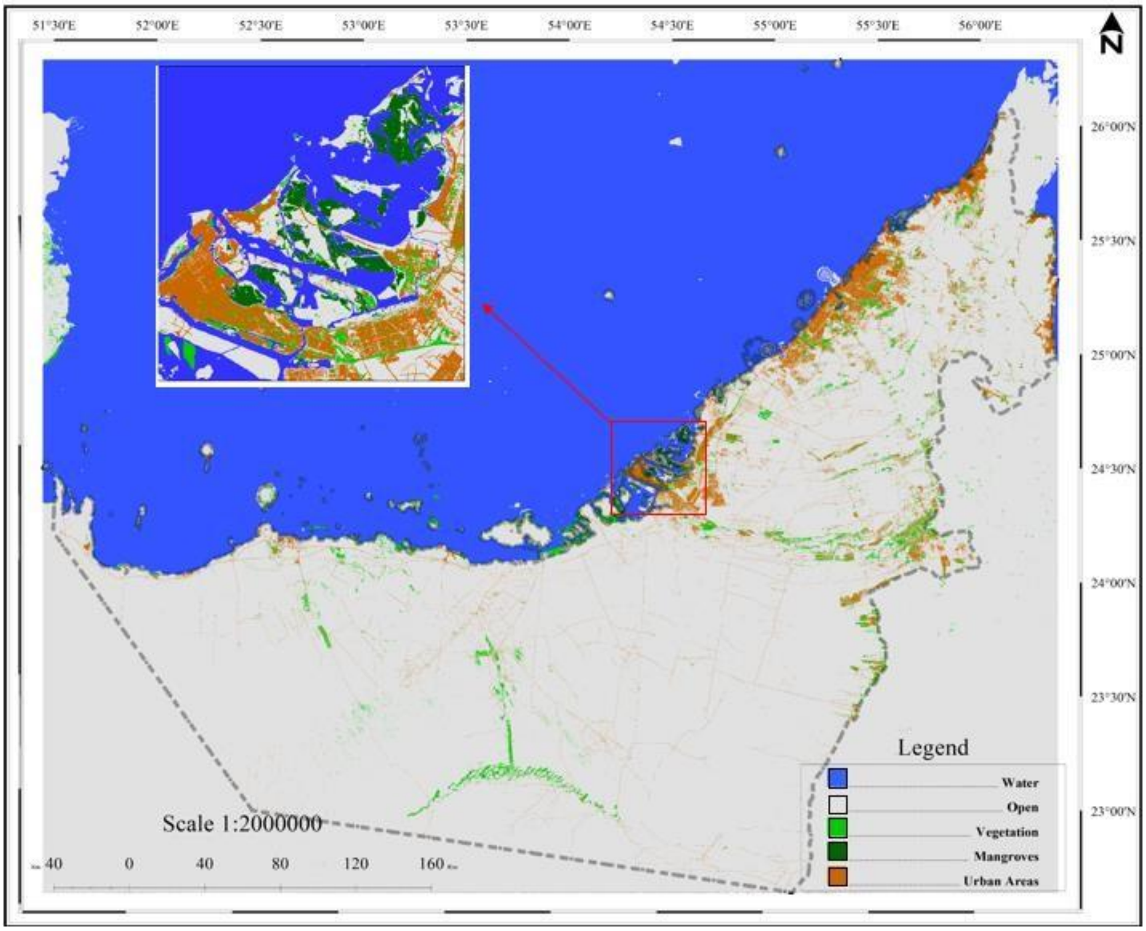


Figure 9: Land use / land cover (LULC) distribution of the UAE.

There were five land covers identified: water, open areas, vegetation, mangroves, and urban infrastructure. Figure 10 shows a confusion matrix that was developed as a means of accuracy assessment for the generated classified image. An overall accuracy of 90.5% was obtained with a kappa coefficient of 0.881. Table 14 displays the latitude and longitude coordinates of the twenty-one testing sites that were chosen in order to produce the matrix below.

```
                         Accuracy Statistics
                         -------------------

Overall Accuracy      : 90.476%    95% Confidence Interval ( 75.540%  105.412%)
Overall Kappa Statistic:  0.881    Overall Kappa Variance :  0.006

Class     | Producer's  95% Confidence   User's  95% Confidence       |Kappa
Name      | Accuracy        Interval     Accuracy    Interval         |Statistic
--------------------------------------------------------------------------------
Water     |100.000%  ( 83.333% 116.667%)  60.000%  (  7.059% 112.941%)| 0.5333


Open      |100.000%  ( 87.500% 112.500%) 100.000%  ( 87.500% 112.500%)| 1.0000


Vegetation      |100.000%  ( 87.500% 112.500%) 100.000%  ( 87.500% 112.500%)| 1.0000


Mangroves | 60.000%  (  7.059% 112.941%) 100.000%  ( 83.333% 116.667%)| 1.0000


Urban |100.000%  ( 90.000% 110.000%) 100.000%  ( 90.000% 110.000%)| 1.0000
```

Figure 10: Confusion matrix for the LULC map.

Table 14: Coordinates of training plots.

Point Number	**Longitude**	**Latitude**	**Class Name**
1.	54.38	24.47	Urban Areas
2.	54.63	24.55	Urban Areas
3.	55.24	25.18	Urban Areas
4.	55.35	25.24	Urban Areas
5.	55.93	25.76	Urban Areas
6.	54.42	24.45	Mangroves
7.	55.32	25.19	Mangroves
8.	55.64	25.55	Mangroves
9.	55.96	25.78	Mangroves
10.	56.37	24.98	Mangroves
11.	54.99	24.73	Vegetation
12.	55.28	24.85	Vegetation
13.	55.43	25.22	Vegetation
14.	53.8	23.21	Vegetation
15.	53.88	23.22	Open
16.	54.23	24.38	Open
17.	53.71	24.18	Open
18.	56.03	25.69	Open
19.	54.3	24.54	Water
20.	55.15	25.23	Water
21.	55.92	25.79	Water

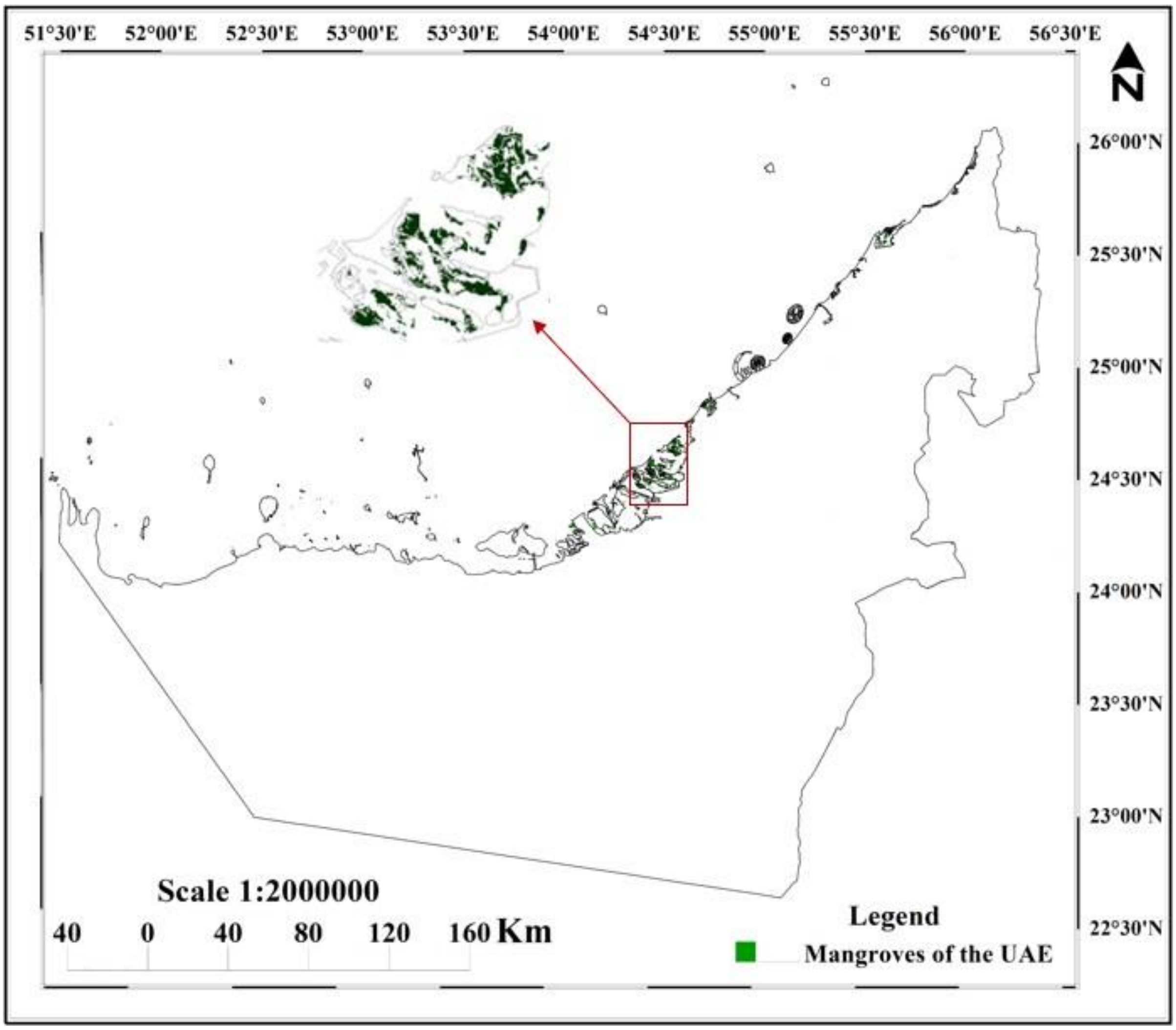


Figure 11: Extent of mangrove forests (mangrove map) distributed across the UAE.

Both maps are generated using Landsat-8-9 satellite imagery from September 2023. Mangrove forests are extracted from other land covers defined in Figure 8 in order to better estimate aboveground biomass across the region using remote sensing techniques. The total extent of mangrove forests in the UAE is approximately 183 km^2 of which 75% of this area belong to Abu Dhabi [48].

The locations of the mangrove forests included on the map on Figure 11 are [45]: Saadiyat Island (Abu Dhabi), Jubail Island (Abu Dhabi), Marawah Marine Biosphere Reserve and Bu Tinah Island (Abu Dhabi), Bu Syayeef Protected Area (Abu Dhabi), Ras Ghurab Island (Abu Dhabi), Eastern Mangrove Lagoon Marine National Park (Abu Dhabi), Al Reem Island (Abu Dhabi), Ras Ghanada (Abu Dhabi), Sir Bani Yas Island (Abu Dhabi), Ras Al Khor Wildlife Sanctuary (Dubai), Jebel Ali Wetland Sanctuary

(Dubai), Mangrove and Al Hafiya Protected Area (Khor Kalba – Sharjah), Al Zorah Wetland (Ajman), Al Seanneeah (Umm Al Quwain), Khor Al Beidah Wetlands (Umm Al Quwain), Khor Mazahimi (Ras Al Khaimah), Mangrove (Ras Al Khaimah), and lastly Seih Al Qurm (Ras Al Khaimah).

5.5.3 AGB Estimation Model from Vegetation Indices

Table 15 shows Landsat-8-9 derived values of 4 vegetation indices (SR – NDVI – EVI – SAVI) and the corresponding AGB values for each sample plot location visited. Since the VIs are derived from Landsat-8-9 at specific latitude and longitude coordinates, their values shown below are per individual pixel. Hence, it is best to convert the units of AGB to Kg / Pixel in order to have uniform units. [1 Landsat Pixel = 900 m^2]

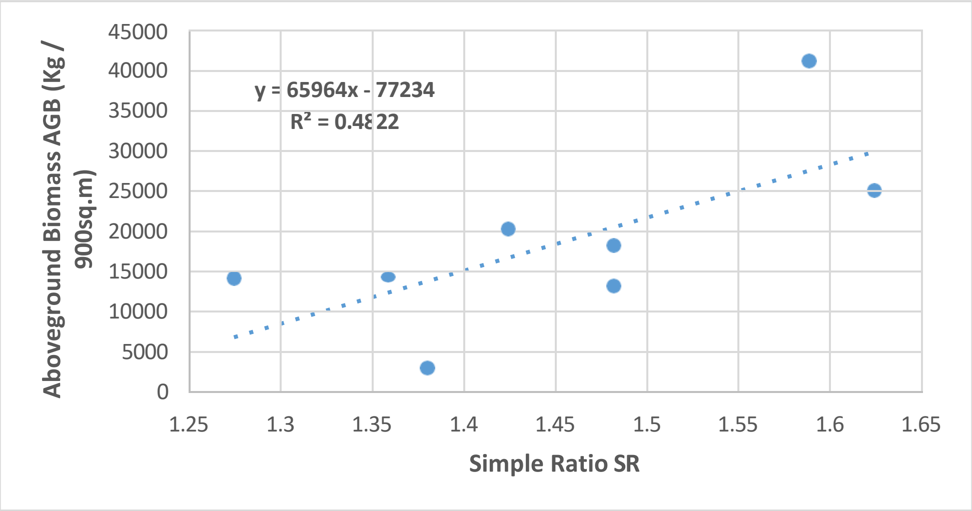
Table 15: Derived values of VIs and AGB.

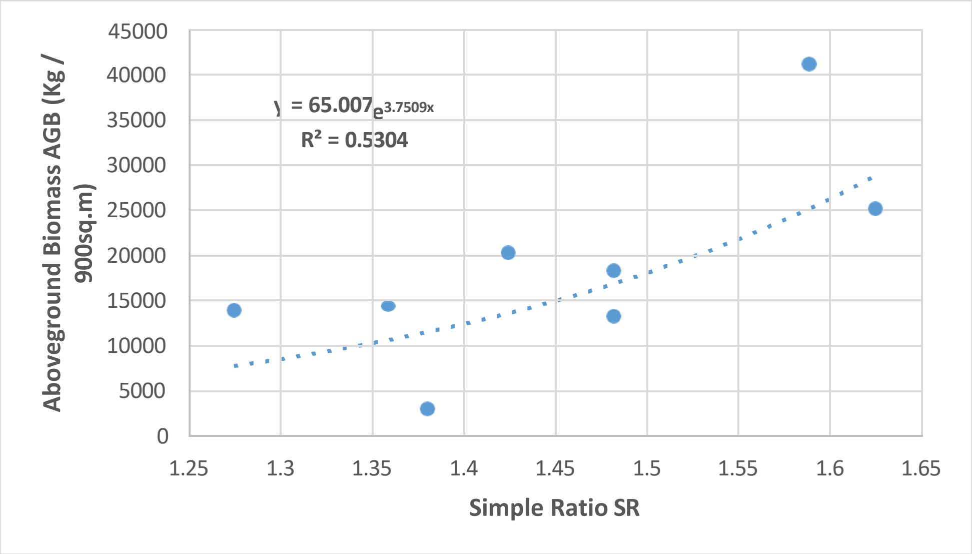
Location	**Sample Plot**	**AGB (Kg / Pixel)**	**SR**	**NDVI**	**EVI**	**SAVI**
Abu Dhabi	1.	12991.20	1.48173	0.194109	0.578805	0.29116
Abu Dhabi	2.	25119.28	1.62453	0.237959	0.655385	0.356933
Abu Dhabi	3.	18036.80	1.48173	0.194109	0.578805	0.29116
Ajman	1.	2748.23	1.37985	0.159612	0.539026	0.239415
Ajman	2.	20236	1.42395	0.1749	0.643866	0.262346
Ajman	3.	40972.72	1.58851	0.227353	0.892093	0.341025
Sharjah	1.	75048.12	1.21796	0.0982713	0.418465	0.147405
Sharjah	2.	14428.44	1.3584	0.151969	0.60324	0.22795
Sharjah	3.	13637.48	1.27431	0.120614	0.469897	0.180918
Sharjah	4.	81774.36	1.21796	0.0982713	0.418465	0.147405

Sample plots 1 and 4 in Sharjah are omitted from this analysis as they are considered outliers. The values of all four vegetation indices at these two locations are relatively low compared to other sample plots which does not coincide with our expectations. We do expect high values of indices for these large mangrove trees. An explanation could be that the satellite not only ‘sees’ the mangrove tree but also mostly surroundings such as soil which could diminish values. Also, these two data points have very large AGB values which might disturb or offset the analysis. For these reasons, it was decided to neglect these points moving forward.

We experimented with various regressions (linear, exponential, and power) of aboveground biomass AGB (Kg / Pixel) versus each of the four vegetation indices selected using values from Table 15 above. The purpose of this method is to be able to find the best regression model in order to estimate AGB of mangrove forests within the UAE. Figures 12 – 15 display the results of each regression model.

Simple Ratio SR





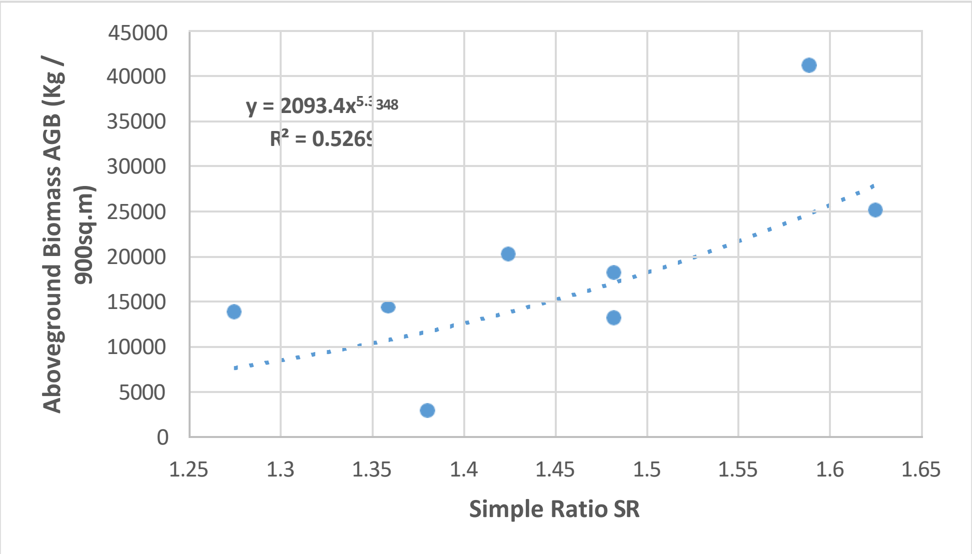


Figure 12: AGB (Kg / Pixel) vs. SR.

Normalized Difference Vegetation Index NDVI

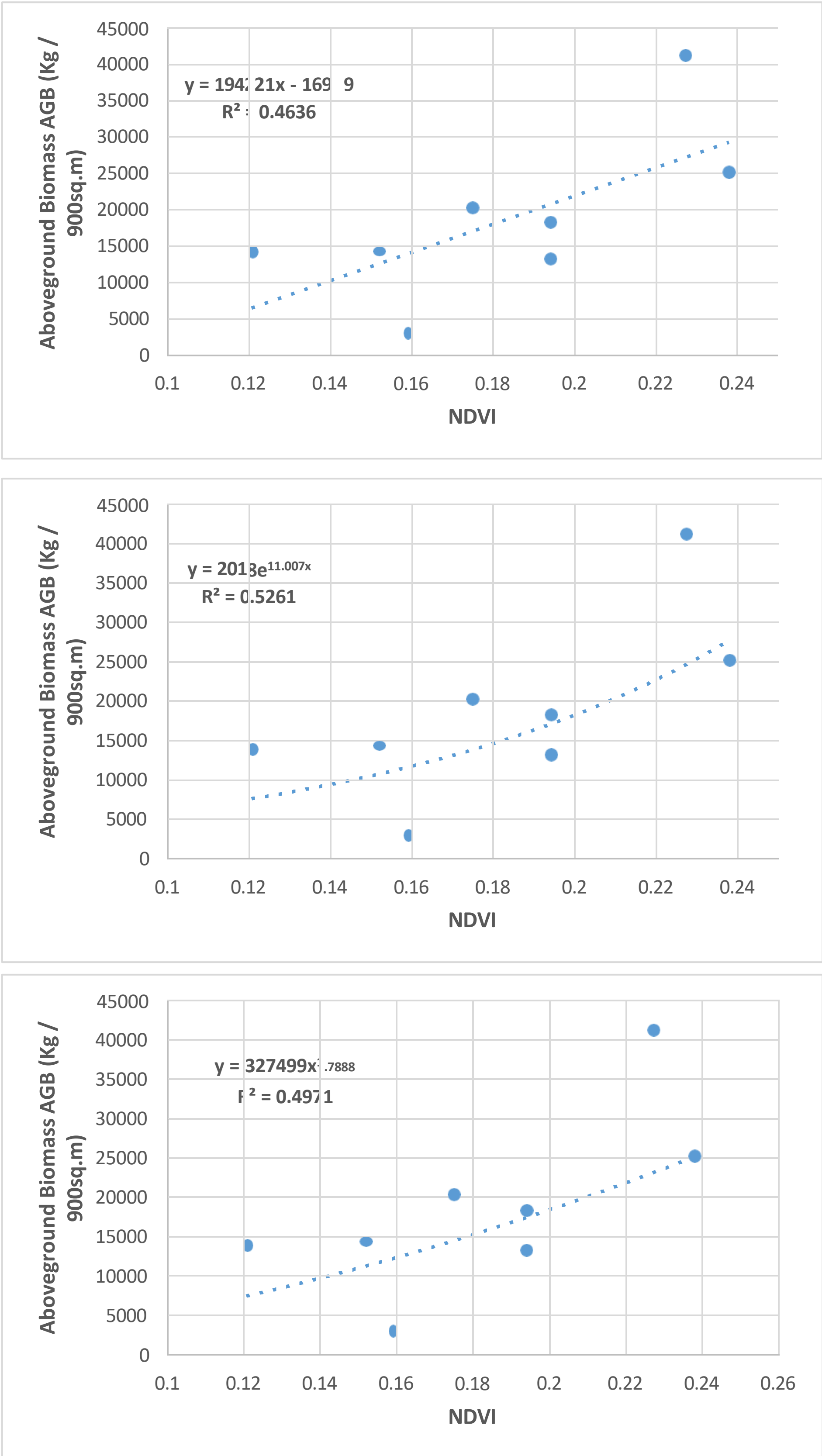


Figure 13: AGB (Kg / Pixel) vs. NDVI

Enhanced Vegetation Index EVI

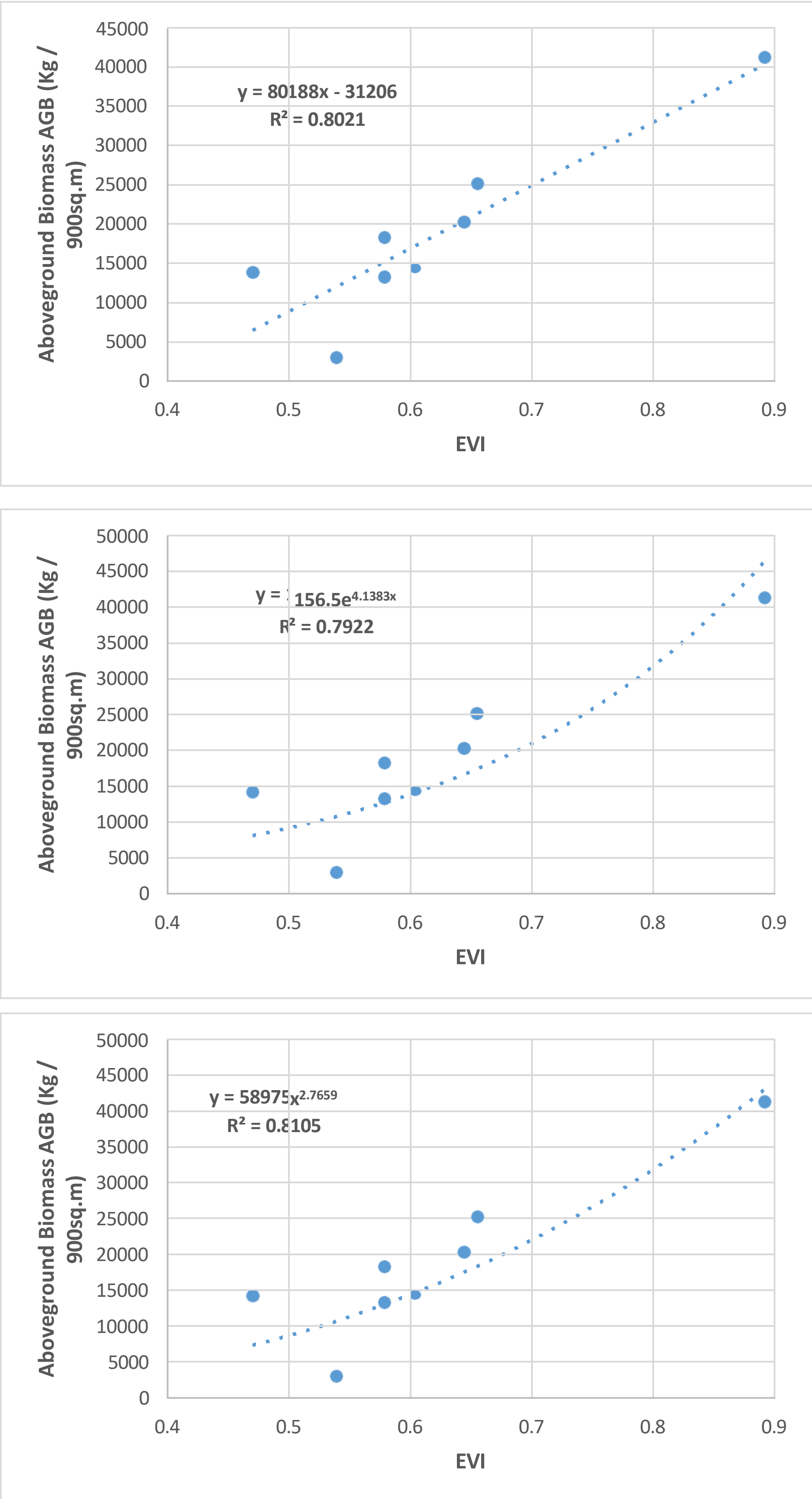


Figure 14: AGB (Kg / Pixel) vs. EVI.

Soil Adjusted Vegetation Index SAVI

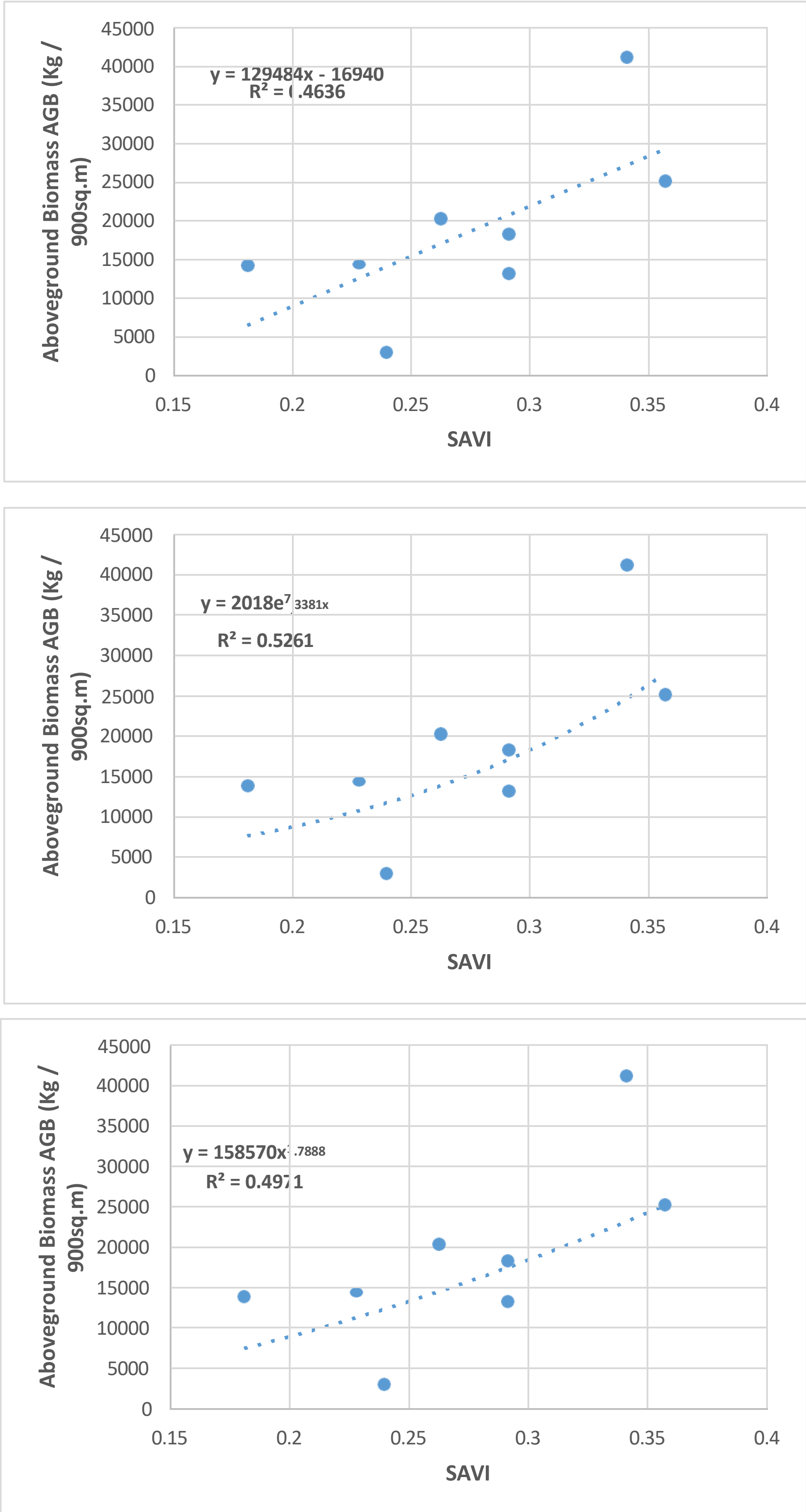


Figure 15: AGB (Kg / Pixel) vs. SAVI.

The Enhanced Vegetation Index (EVI) had the best performance in all three scenarios. The highest value of the coefficient of determination (R^2) was obtained when utilizing a power regression with EVI based on the twelve plots shown above. Hence, the best model for AGB estimation based on Landsat-8-9 data and field work biomass values is as follows:

$$\text{AGB} = 58975\ \text{EVI}^{2.7659}$$

This power equation has an R^2 value of 0.8105 with a p-value < 0.005. Therefore, this model was used to estimate AGB of mangrove forests across the UAE. Table 16 below summarizes the validation of the selected model.

Table 16: Validation of selected AGB estimation model.

Location	**Sample Plot**	**AGB Estimation - Allometric Equation (Kg / Pixel)**	**AGB Derived Model Estimation (Kg / Pixel)**	**Percentage Error (%)**
Abu Dhabi	1.	12991.20	12997.38	0.05
Abu Dhabi	2.	25119.28	18328.02	27.0
Abu Dhabi	3.	18036.80	12997.38	28.0
Ajman	1.	2748.23	10674	288.4
Ajman	2.	20236	17450.80	13.8
Ajman	3.	40972.72	43003.85	5.0
Sharjah	2.	14428.44	14572.22	1.0
Sharjah	3.	13637.48	7302.31	46.5

Based on Table 16, the agreement of the model was studied by calculating the error between calculated and derived AGB. As a result, the percentage error ranges from 0.05% to 288.4% with an average error of 22%. Sample 1 in Ajman has a high error due to the fact that this mangrove tree was on the outskirts of the forest and perhaps is an outlier as well; It does have a relatively low DBH value compared to others. If this data point is temporarily removed, the average percentage error becomes 15.6%. Hence, the selected AGB estimation model is relatively appropriate and can be applied to all mangrove forests across the UAE.

Predicting AGB using remote sensing techniques is of vital importance to industries related to forest management and conservation, climate change mitigation, and sustainable development [12], [16], [52]. Accurate aboveground biomass and carbon concentration of a particular mangrove area can be obtained from field work. However, this may be difficult due to restrictions in time, access, etc. and may involve destructive procedures to the mangrove trees (Ex: deforestation). For these reasons, it is essential to estimate mangrove biomass using remote sensing predictors such as VIs.

5.5.4 Generation of AGB and AGC Maps

We input our selected model into the Raster Calculator to compute aboveground biomass over all mangrove areas across the UAE. Biomass categories were created based on inspected histogram of values and an AGB map was generated as shown in Figure 16.

The aboveground carbon AGC map displayed in Figure 17 was generated in a similar way. The following equation

$$\mathrm{AGC} = 0.47 \times \mathrm{AGB}$$

was applied to the entire biomass raster and AGC categories were obtained by studying the corresponding histogram of pixel values.

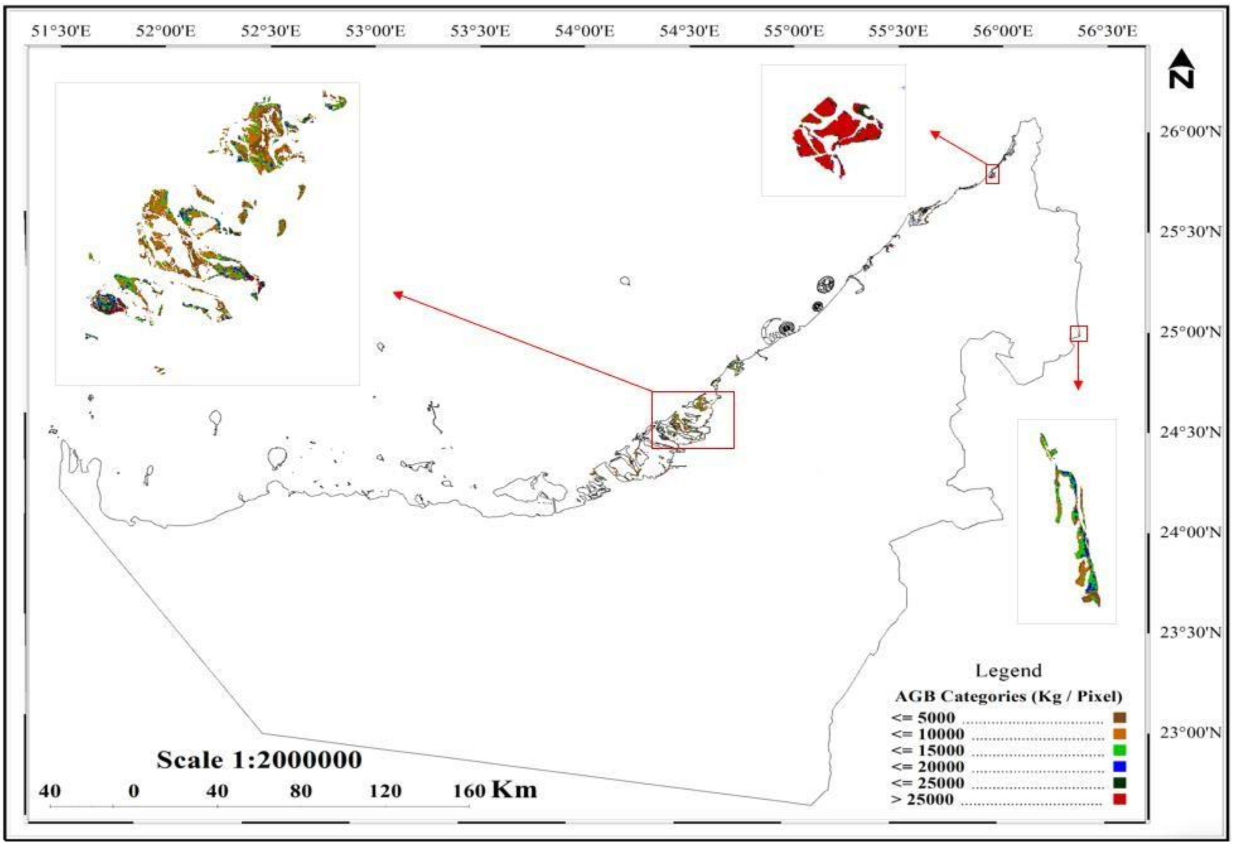


Figure 16: Spatial distribution of AGB categories across the emirates of the UAE.

AGB values were classified into six categories: ≤5000 Kg, ≤10,000 Kg, ≤15,000 Kg, ≤20,000 Kg, ≤25,000 Kg, and >25,000 Kg. These values are shown per individual pixel. Three locations are used as zoom-ins to depict the range of biomass values. The mangrove forest in Ras Al Khaimah [top-right] predominately shows biomass values greater than 25,000 Kg. Segments of Abu Dhabi show the same while most areas lie in the range of 0 – 20,000 Kg in aboveground biomass.

The total biomass across mangrove trees in the entire UAE is estimated to be 1902653231 Kilograms = 1,902,653.231 Tons = 1,902.653231 Kilotons. The lowest AGB value was found to be 2.4×10^{-5} Kg with a maximum AGB value of 118,709 Kg or 118 Tons per 900 m^2 (1 Landsat pixel).

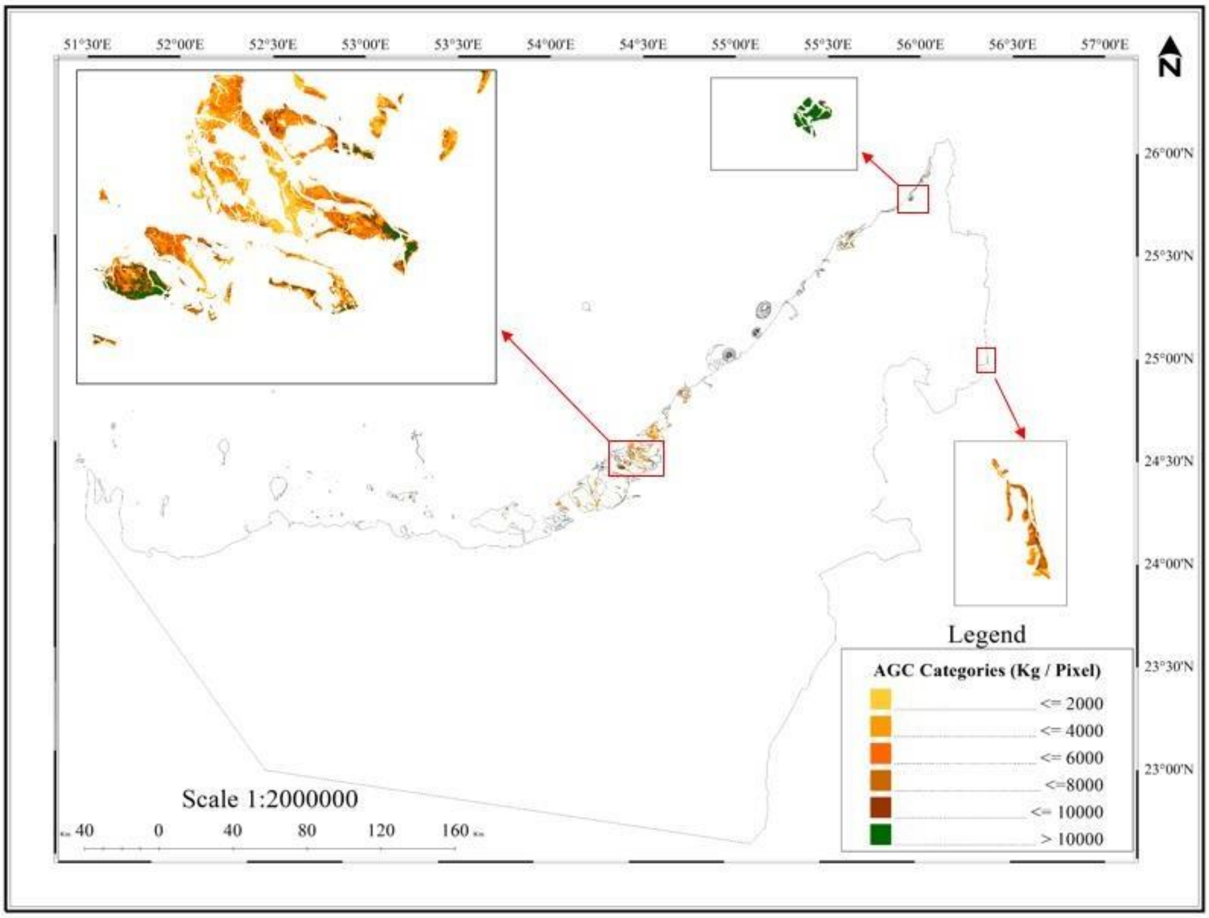


Figure 17: Distribution of aboveground carbon (AGC) across the coasts of the UAE.

Similarly, AGC values were divided into six categories: ≤2000 Kg, ≤4000 Kg, ≤6000 Kg, ≤8000 Kg, ≤10,000 Kg, and >10,000 Kg. The total carbon stored in mangrove forests across the UAE is estimated to be 894,246,882 Kilograms = 894,246.882 Tons = 894.2469 Kilotons. The lowest AGC value was 1.13×10^{-5} Kg with a maximum value of 55,793.3 Kg.

Biomass and carbon values across mangrove forests of different emirates are approximated using Catalyst Earth software and are summarized in Table 17 below. The intention is to be able to clearly see where the biomass and carbon are distributed throughout our study area.

Table 17: Results of biomass and carbon across different emirates of the UAE in kilotons.

	Abu Dhabi	**Dubai**	**Sharjah**	**Ajman**	**UAQ**	**RAK**
AGB	1443.414	19.95	16.81	61.81	240.38	117.2
AGC	678.404	9.378	7.9	29	113	55.13

The results above are shown in Kilotons for a better understanding of each value. Since Khor Kalba (Sharjah) is the oldest mangrove forest in the UAE, it is expected to store the maximum amount of biomass as well as carbon. Nevertheless, this was not the case; we seem to have the lowest values. This is due to the fact that we omitted 2 of the 4 data points belonging to this site location. It is recommended to 1. Collect more measurements from each site visited, 2. Visit more mangrove forests during the field work, or 3. Build AGB models for individual site locations to obtain the most accurate results. However, the model selected for this study is appropriate for estimations. Abu Dhabi contains the largest amount of biomass and carbon stored with values of 1443.414 and 678.404 Kilotons respectively. This is evident since the capital contains 75% of the total mangroves of the UAE. Figure 18 displays a pie chart of the results obtained above for better visualization.

Mangrove forests across the world have different characteristics than those in the UAE in terms of species and soil for instance. This is why the AGB model should only be utilized for biomass estimations across the same study area as in this research. A general model cannot be accurate on a large scale [16].

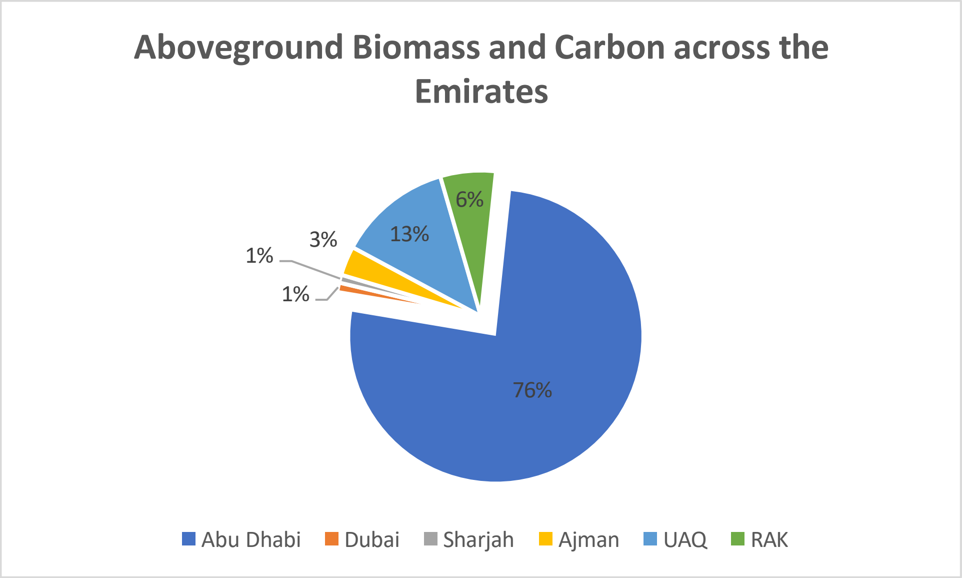


Figure 18: Percentage of AGB and AGC in mangrove forests across UAE emirates.

Chapter 6: Conclusion and Recommendations

6.1 Summary of Research Project

This research project aims to establish a model to estimate aboveground biomass (AGB) as well as carbon concentration of mangrove forests across the United Arab Emirates by combining the use of Landsat-8-9 remote sensing data with field work measurements. The results and findings of this study may be utilized as a base or standard methodology for similar studies of the Arab Satellite 813 to be launched in Q1 of 2025. Additionally, it can assist relevant authorities in taking necessary actions for sustainable management and expansion of mangrove forests in the UAE.

This study began with the collection of in-situ measurements of Avicennia Marina at three site locations namely Eastern Mangrove (Abu Dhabi), Al Zorah (Ajman), and Khor Kalba (Sharjah). Direct and calculated parameters obtained include Tree Height (m), Diameter at Breast Height DBH (cm), Basal Area (m^2), Aboveground Biomass AGB (tons / hectare), and Aboveground Carbon AGC (tons / hectare).

Spaceborne Landsat-8-9 satellite digital imagery data acquired in September 2023 were used for Earth observation remote sensing techniques such as image data analysis and interpretation. Then, 12 AGB estimation models were developed based on a combination of field work biomass calculation and four Landsat-8-9 derived vegetation indices, specifically SR, NDVI, EVI, and SAVI. In this particular study, the best AGB estimation model with the highest coefficient of determination (R^2 = 0.8105) was obtained using the Enhanced Vegetation Index $AGB = 58975\ EVI^{2.7659}$ with an average percentage error of 22% [between AGB-calculated and AGB-derived]. Therefore, this model was used to estimate AGB of mangrove forests within the entire UAE as well as the individual emirates. The total mangrove biomass was estimated to be 1,902,653.231 tons while the total carbon stored in mangrove forests in the UAE was approximately 894,246.882 tons.

6.2 Uncertainties, Improvements, Recommendations and Future Work

Uncertainties may rise in this research study due to several factors. Improvements to the current methodology as well as future enhancements can greatly increase the accuracy of biomass estimation of mangrove forests.

1. Due to weather conditions in the UAE, muddy environments, and inaccessible forests, in-situ data collection was limited. Overall, 10 sample plots at 3 site locations were visited which is not adequate for a statistical study. Therefore, increasing the number of sample plots would increase the accuracy of AGB estimation. Moreover, the allometric equation used to calculate biomass of Avicennia Marina is not specific to the United Arab Emirates [12]. Improvements and future work can include the development of such equations by measuring the dry weight of different mangrove trees of all sizes belonging to the UAE.
2. Landsat-8-9 satellite imagery from September 2023 was utilized for this study. Uncertainties such as the 30m spatial resolution and possible cloud cover obscuring can lead to misclassification in the LULC map. The use of high-resolution remote sensing data in 2023 as LiDAR data would provide more accuracy in image data analysis. A further improvement would be to build digital elevation and terrain models to map areas of mangrove forests that are facing threats against sea level rise [12], [16].
3. SR – NDVI – EVI – SAVI are the four vegetation indices computed over the mangrove raster. The use of more VIs in particular Leaf Area Index which measures the quantity of leaf material in a canopy and Mangrove Vegetation Index that provides information on mangrove greenness and moisture, can assist in building a more accurate biomass estimation model. Moreover, the selected model was chosen based on a regression between [allometric equation] AGB and the four derived indices. An enhancement to this method would be the use of multivariate statistics; adding DBH or multiple indices as variables to strengthen the model [53]. Additionally, exploring the use of machine learning integrated into our techniques may improve correlation results.

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This thesis project aims to estimate the aboveground biomass of mangrove forests across the entire UAE using spaceborne remote sensing techniques. The results and findings should benefit the Arab Satellite 813 and assist relevant authorities in taking any necessary actions.

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