Spring 2021

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SIT Study Abroad

Recommended Citation

Ytterdahl, Bailey, "Assessing and Mapping the Spatial-Temporal Change in Forest Phenology of Arabuko-Sokoke Forest using Moderate Resolution Satellite" (2021). *Independent Study Project (ISP) Collection*. 3377.
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Assessing and Mapping the Spatial-Temporal Change in Forest Phenology of Arabuko-Sokoke Forest using Moderate Resolution Satellite

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Gettysburg College, SIT Tanzania and Kenya Spring 2021

ACKNOWLEDGEMENTS

I would first like to thank our amazing program staff, coordinators and academic directors, Dr. Oliver Nyakunga, Oscar Paschal, Kaiza Kanganzi and Mama Juni. With all the changes thrown at this group this semester with the global pandemic, you all deserve the world. We really appreciate everything you have done for us, especially squeezing in the Serengeti and Ngorongoro experience before we had to leave for Kenya. From Tanzania to Kenya and wherever after, you all were always there for us to help us transition. Not only have you all, but this program has taught me various life skills, like being resilient and adaptability. Even though you were not with us long in Kenya, we missed you every day and appreciate everything you did to help us with ISP and on a daily basis. Thank you for constantly helping me stay levelheaded during ISP since I was very overwhelmed with all the changes of the program and data analysis at times. You all always worked after hours and put in your full effort and assistance at any time.

I would also like to acknowledge those on the Kenya SIT team who helped us transition to another country. I want to thank Milton and Dr. Steve Wandiga for being there and setting up all the local connections in Kilifi. Another massive thanks to Dr. Rose Kigathi at Pwani University in Kilifi, who assisted in finding us mentors for ISP, identifying topics, as well as coordinating our excursions. Dr. Rose was also one of my three advisors who assisted me with this more complicated analysis. Additionally, Dr. Mohammed Yahya Said was a massive help to my study project. I never have done quite an analysis like this before in GIS, and he helped me through the methods and analysis carefully. I am sure you were extremely busy, but I greatly appreciate the time and effort you put into my project to assist me. It would never have been completed without your immense help.

Next, I want to acknowledge the numerous individuals that work at Makuti Villas. They never stopped showing us their immense hospitality for the last month and a half that we were living there before we were sent home. The environment was perfect for working, studying, and relaxing by the pool. Lastly, I want to highlight the individuals who drove and guided us to our different excursions in Arabuko Sokoke, Watamu, Mombasa, and Mida Creek. Without them, we all would not have been able to conduct data collection for ISP or find our interests in such a new area. Thank you everyone for a great semester, even with all the changes, it has been one of the best semesters I have ever had in college and it will stay with me for the rest of my life. I hope I get to return to Kenya/Tanzania in the near future to explore more since our time was unfortunately cut short.

ABSTRACT

This study focuses on coastal forests in Kenya that have some of the highest variety of flora and fauna, specifically Arabuko Sokoke Forest. Arabuko Sokoke Forest is located 110 miles north of Mombasa and 18 kilometers south of Malindi. This forest is known to be a worldwide biodiversity hotspot that is home to endemic and rare plants and animals. Within the Arabuko Sokoke Forest ecosystem, there are two main issues that challenge the conservation of the area. First, there has been more competition for land, primarily for agriculture and development. Second, there is an increase demand for forest resources due to the rise in population. Therefore, this study aims to assess the spatial-temporal change in forest phenology over time around Arabuko Sokoke from 2003-2020 using the remotely sensed Vegetation Condition Index (VCI) and ground information. The specific objectives are to map spatial-temporal changes in forest phenology over the last 18 years of Arabuko Sokoke Forest; and to analyze the change of vegetation condition in combination with ground experiences to understand pressure and drivers of changes in order to develop future policy actions to minimize the deterioration. Based on the problems posed in Arabuko Sokoke Forest, I hypothesized there will be an immense change in vegetation phenology in the last 18 years driven mostly by climatic changes in addition to anthropogenic pressures. MODIS images were used to map the environmental changes over 5 distinct seasons: annual, long dry season (DJFM), long rainy season (AMJJ), short dry season (AS) and short rainy season (ON) from 2003- 2020. The vegetation condition index (VCI) was mapped in QGIS to visually represent the trends of each season over 18 years. Many of the years were consistent in trends in terms of vegetation health. The years 2007, 2016, 2017, and 2020, there were significant VCI trends with either low or high VCI grades, different than the other years. 2016 and 2017 in across all 5 seasons appeared to have low VCI grades. However, 2007 was found to have high VCI grades in multiple seasons. Although there may have been anthropogenic impacts at play, it was found that temperature had the largest influence in terms of changing the VCI over time. Future research poses that there should be an investigation of the exact causes of these VCI trends that were mapped. For instance, were they influenced by anthropogenic impacts, limited precipitation, poor policies, climate change, the influence of disease and how biodiversity would be impacted based on these drivers?

KEYWORDS: Vegetation Condition Index, Arabuko Sokoke Forest, Vegetation dynamics, Drought, Population, Degradation

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ABBREVIATIONS

ASF- Arabuko Sokoke Forest

EVI-Enhanced Vegetation Index

KWS- Kenyan Wildlife Service

MODIS-Moderate Resolution Imaging Spectroradiometer

SVI- Standard Vegetation Index

NDVI-Normalized Difference Vegetation Index

VCI- Vegetation Condition Index

WWF-World Wildlife Fund

CHAPTER ONE

1.0 INTRODUCTION

Around 1 billion people worldwide live in and around forests using the resources they provide daily (WWF, 2020). However, due to anthropogenic impacts, the world has lost approximately 40% of its forests, and they continue to decrease drastically each day (WWF, 2020). To understand specifics about forests, the term should be defined. Forests are stated to be "a continuous stand of trees at least 10 m tall, [and] their canopy interlocking" (Peltorinne, 2004). The importance of global forests should not be underestimated. Not only are forests crucial habitats for billions of species, but they also create livelihoods for people and provide several resources for populations. The different forests around the world offer protection to water sources, prevent soil erosion and minimize climate change by absorbing harmful greenhouse gasses (WWF, 2020).

This study focused on forests in Kenya located in East Africa. Around 3.4% of Kenya's total land area is covered by natural and tropical forests and roughly 15% of potential land (Peltorinne, 2004). Although Kenya has extremely fragmented forest blocks, they are some of the most diverse in East Africa. There are a variety of forests within Kenya depending on the classification of vegetation. Forests in western Kenya include "lowland rain forests, and montane forests in the central and western highlands and on higher hills and mountain along the southern border" (Peltorinne, 2004). There are six distinct forest blocks in Kenya: the high volcanic mountains and high ranges; Western plateau; Northern mountains; Coastal Forests and Riverine Forests. All these forests have distinct features, but the highest diversities occur often in the coastal forests (Peltorinne, 2004). Not only are they diverse in wildlife but are the last remnants of ancient forests that once ranged along the coast of East Africa from Mozambique to Somalia (Peltorinne, 2004). However, coastal forests have been through a long history regarding the human impact that has influenced their fragmentation. This study will focus on Coastal Forests, specifically Arabuko Sokoke Forest in Kenya.

1.1 Problem Statement

Arabuko Sokoke Forest (ASF) is known worldwide to be a biodiversity hotspot due to its high number of endemic and rare plants and animal species. This forest is the largest remaining single block of ancient coastal forest in East Africa covering around 41,600 hectares of land (Forest Management Plan Team, 2002). This forest consists of 20% of the bird species and 30% of butterfly species in Kenya (Forest Management Plan Team, 2002). It is currently managed by three partnerships which include the Kenya Wildlife Service, Kenya Forestry Research Institute and National Museums of Kenya. While Arabuko Sokoke Forest needs to be conserved, there are numerous threats and challenges posed to this area. Currently, there are approximately 54 villages that surround the forest who depend upon the various resources (Forest Management Plan Team, 2002). With the increasing population, there is land competition and many of the lowland forests are transformed to agriculture (Forest Management Plan Team, 2002). Unfortunately, forest officials have also observed increased amounts of illegal harvesting of resources, such as commercial logging, charcoal, bushmeat and species for woodcarvings (Forest Management Plan Team, 2002). Similarly, the weak governance of various management groups does not help to reduce the threats (Forest Management Plan Team, 2002). Additionally, previous research has assessed reasons for disturbances, forest cover loss as well as trends of biodiversity decrease, but no study has conducted to analyze vegetation phenology and how it has changed over time. There has also been limited studies that include spatial-temporal change using moderate resolution satellites. Therefore, this study aims to assess the spatial-temporal change in forest phenology over time of Arabuko Sokoke from 2003 to 2020 using the remotely sensed Vegetation Condition Index (VCI). The specific objectives are:

1.3 Objectives

1.4 General objectives

To Assess and Mapp the Spatial-Temporal Change in Forest Phenology of Arabuko-Sokoke Forest using Moderate Resolution Satellite.

1.5 Specific objectives

i. To map spatial-temporal changes in forest phenology over the last 18 years of Arabuko Sokoke Forest.
ii. To analyze the change of vegetation condition in combination with ground experiences to understand pressure and driver of change in order to develop future policy actions to minimize the deterioration.

1.6 Hypothesis

Based on the problems posed in Arabuko Sokoke Forest, I hypothesize that there will be an immense change in vegetati

on phenology in the last 20 years, especially between 2015 and 2020.

CHAPTER TWO

2.0 LITERATURE REVIEW

Throughout the region where Arabuko Sokoke resides, rural communities have exploited the resources for centuries. However, the exploitation and degradation of the forest has become unsustainable during the last 60 to 70 years (Kirongo et al, 2003). At the moment, there are major threats and phenomena impacting the phenology of the vegetation. For instance, the population growth, unsustainable land use, illegal activities, climate change and weak policy and governance.

2.1 Population Increase

Arabuko-Sokoke Forest (ASF) is one of the last remaining single blocks of ancient dry coastal forest that was once extensive along the East African Coast. Currently, there are approximately 54 villages that surround the forest with a population of around 104,000 people (Forest Management Plan Team, 2002). Most of these individuals depend on the resources from the forest. However, this region is notable for the high population density adjacent to the forest (Habel et al, 2017). For instance, the population density of the surrounding counties was found to be 229.1 people/km^2 in comparison to the coastal regions with 74.8 people/km^2 or a mean number of 66.4 people/km^2 throughout Kenya (Habel et al. 2017). Similarly, the two neighboring counties of the forest, Kilifi and Malindi, had a human population growth rate of more than 4.4% between 1999 and 2009 (Habel et al. 2017). With the continuously increasing population around Arabuko, there is expanding pressure to forest resources and the biodiversity. It is also important to acknowledge that individuals living within a 5-kilometer distance of the forest have the legal right to access the benefits of the forest (Habel et al. 2017). Therefore, as the growth rate rises in the buffer zone, the more resources will be depleted, making the necessity to conserve the flora and fauna stronger.

2.2 Land Use and Issues

As of today, many of the people that live adjacent to the forest are small scale farmers or others that depend on the forest to provide them a livelihood (Habel et al. 2017). Since many individuals are dependent on this lifestyle, land ownership is crucial to economic and human development (Shurmann et al. 2020). By securing access to land, people have the ability to increase their living conditions within society, gender equity, and to invest in more sustainable land use (Shurmann et al, 2020). While there are positive impacts on the surrounding population with the plethora of resources, with the increasing population in the need for more land, there are threats growing in the community. Previous studies have found that over time, there has been decrease in size of land parcels, but also an increase in the proportion of agricultural lands (Teucher, 2016).

For the Arabuko Sokoke Forest, there are two primary issues that jeopardize conservation. As it was just stated, there has been more competition for land, primarily for agriculture and development. Secondly, there is an increasing demand for forest resources (Forest Management Plan Team, 2002). In the Arabuko Management Plan for 2002 to 2027, there are nine themes that represent the major issues or concerns to the protected area: biodiversity conservation, subsistence use, ecotourism and environmental education, problem animal management, forest protection, commercial use, infrastructure development, human resource development and research and monitoring (Forest Management Team, 2002).

Arabuko Sokoke Forest is a crucial ecosystem to the unique number of flora and fauna along the coast. However, the nine major issues that the ASF Management Plan acknowledges can contribute to the deterioration of the forest cover, quality of the forest resources and endangers biodiversity. For instance, previous studies have found that some tree species, such as *Brachylaena huillensis,* are having a difficult time regenerating. In the past, since *Brachylaena huillensis* was used for selective harvesting for decades, there are concerns for the future health of this species since it is a dominant specie in certain zones of the forest (Forest Management Plan Team, 2002). The removal of dry wood reduces the number of important invertebrates, such as termites and beetles, which will ultimately have a chain reaction affecting the bird population (Forest Management Plan Team, 2002). The altering of the forest composition, cover, and structure, then affect the birds, insect and animal species that are already possibly threatened (Forest Management Plan Team, 2002). Similarly, subsistence use is the largest threat to the forest's species and biodiversity, but at the same time is important to the surrounding villages. Since the growing populations are dependent on the forest for their livelihoods, the medicinal plants, bushmeat, firewood, and building materials, the resources are deteriorating drastically. This unsustainable use of resources is an unfortunate cause of poverty and the necessity for the resources (Forest Management Plan Team, 2002). It has been acknowledged that the more poverty that is present, the more dependent individuals are on the forest resources (Forest Management Plan Team, 2002). It also does not help the relationship with the forest due to the problem animals, such as monkeys, baboons and elephants that raid crops in the surrounding communities. This causes a hostile relationship between the forest organizations and the locals towards conservation. Therefore, since conservation will restrict the use of materials for their livelihoods, at times there is not much local support for forest protection (Forest Management Plan Team, 2002). Other concerning issues include commercial harvesting as well as illegal activities. It has been identified that the commercial timber industry in the past has contributed to its degraded state. Although there is only a small portion of the forest, around 700 hectares that would still be viable for commercial use, the stress of it previously impacted Arabuko Sokoke in the long run (Forest Management Plan Team, 2002). One study found that the southern half of the forest was where the majority of the cutting occurred (Waters, Jackson and Jackson, 2007). Researchers indicated that this part was farthest from the main headquarters of the forest, possibly having different patrolling than in the northern sections (Waters, Jackson and Jackson, 2007). By the Arabuko Management team focusing on these main nine issues within the forest and the adjacent community, there is hope for the future conservation and protection.

2.3 Climate Change

Despite the pressures of land use, deforestation and illegal harvesting that face Arabuko Sokoke Forest, there has been predicted impacts of climate change on the forest ecosystems in Kenya (Tarus et al, 2018). Climate change is having the potential to impact the composition, growth rates and regenerative capacity (Tarus et al, 2018). Since Arabuko Sokoke is in close proximity to the ocean, the vulnerability of it is higher because of predicted sea level rise (Tarus et al, 2018). According to a study done by George K. Tarus et al. (2018), in the Climate Change Program of the Kenyan Forest Service, he studied to determine the accumulation rate of biomass in the three dominant vegetation types and how climate change would impact its distribution (Figure 2). Their results show that the biomass relates significantly with patterns of rainfall as well as maximum and minimum temperatures (Tarus et al, 2018). Not only did they present that biomass accumulate over time, but the study indicated that "there was significant temperature and rainfall variability between 1990 to 2013 in Arabuko Sokoke Forest" (Tarus et al, 2018). Therefore, depending on these factors, climate change would drastically impact the distribution of the different forest types throughout the forest over time. This added threat of climate change along with the other more direct threats to the forest will not only impact the vegetation but can also correspondingly impact the immense biodiversity in the forest.

2.4 Administrations

There are four government departments that work for the protection of Arabuko Sokoke. These are the Forest Department, Kenya Wildlife Service, Kenya Forestry Research Institute, and the National Museums of Kenya. Additionally, there is another organization named the Senior Management Committee that overlooks the daily actions of each group (Forest Management Plan Team, 2002). The combination of all these four working groups and the Senior Management Committee makes up the overall Arabuko Sokoke Management Team. The four working groups are: Forest management working group, rural development, tourism and education, and research and monitoring (Forest Management Plan Team, 2002). While these are national level organizations, there are also local non-governmental organizations, such as Friends of Arabuko Sokoke and Forest Adjacent Dwellers Association (FADA) that assist with many of the conservation objectives and local involvement (Forest Management Plan Team, 2002). With this forest being one of the most unique ecosystems in the world, international organizations have also taken part in the conservation. For instance, Birdlife International, that is a partnership with many conservation NGOs and is based out of the United Kingdom, has worked alongside the Arabuko management team since 1983 (Forest Management Plan Team, 2002). The conservation team of Arabuko Sokoke Forest is made up of multiple stakeholders for the possibility of strengthening the protection of the unique ecosystem.

2.5 Strategies, Policy and Governance

To achieve proper protection, the management team took the nine primary threats to the forest and identified strategic management objectives and actions that should be taken over the next 25 years. There were multiple actions and policy suggestions for each strategic objective, with some overlap for the varying threats (Forest Management Plan Team, 2002). Important strategies and actions to highlight are the significance of environmental education and awareness. For instance, to address the loss of biodiversity, some actions include the involvement of locals in research projects as well as ecotourism endeavors (Forest Management Plan Team, 2002). One of the most important issues of subsistence use proposes the actions of poverty reduction through alternative livelihoods, such as butterfly farming and beekeeping. These other incomes are non-consumptive in the forest community to display that it is possible to live a more sustainable lifestyle (Forest Management Plan Team, 2002). To continue to conserve the forest and its resource for the future, it was notable that a cohesive relationship between governmental organizations, local villages and non-governmental groups are important for decision making. Additionally, having the proper infrastructure, such as fences, to protect individuals from human-wildlife conflicts as well as roads, buildings, and services for promotion of ecotourism and conservation (Forest Management Plan Team, 2002).

Although there are specific planning of strategies and policy proposals for the next 25 years, the governance of the forest is also important to note. Governance includes the various organizations that are involved in making the decisions for management strategies but carrying out actions are bestowed on other groups of stakeholders (Forest Management Plan Team, 2002). At times, the collaboration between multiple stakeholders can be difficult. While many projects have worked well in the past, there have been occurrences that some projects have “tried to force pre-conceived ideas on what they want to support and how it is to be done unilaterally” (Kirongo, Mbuvi and Wairungu, 2003). However, these actions have left some communities in worse conditions than they were previously, creating cynical views of forest organizations. Therefore, in the future, it is important to have reform in the governance and to facilitate good and effective collaboration, for there needs to be trust or a solid relationship between governmental organizations, non-governmental, and local villages (Kirongo et al, 2003). The needs and interests of all people should be considered when making executive decisions (Kirongo et al, 2003). Additionally, Arabuko Sokoke Forest is a biodiversity hotspot and center for socio-economic activities that needs effective management and policy to be conserved for the current and future generations. With efficient management and collaboration with the adjacent communities, there are hopes of the anthropogenic threats and other issues to be minimized in the future.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Study Area

The Arabuko Sokoke Forest is a 420-kilometers squared block of forest located between 3.3278° S, 39.8749° E along the Kenyan coast (Oyugi et al. 2007). It lies 110 kilometers north of Mombasa and 18 kilometers south of Malindi (Figure 1; Oyugi et al. 2007). The eastern part of the forest is on a flat coastal plain at an altitude of around 45 meters above sea level. On the other hand, the central and western part of the forest lie on a plateau about 60 to 200 meters. The annual rainfall ranges from 1000 millimeters in the east to 600 millimeters in the northwest part of the forest, with the long rains between April to June and short rains from November to December (Forest Management Plan Team, 2002).

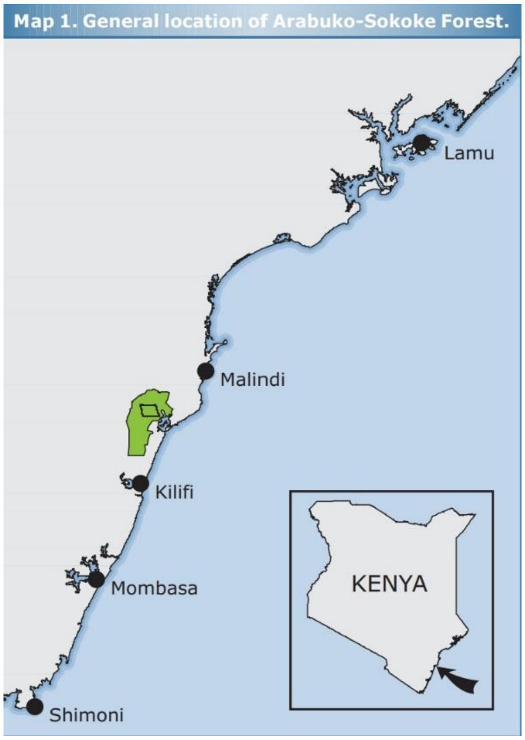


Figure 1. The general location of Arabuko Sokoke Forest along the East African Coast of Kenya. This map is from the Arabuko Management Plan for 2002-2027.

In this coastal forest, there are three major vegetation types (Figure 2). The Mixed Forest, which is a thick flora located on the east side in the wetter sands and extends over 7000 hectares. There are diverse tree species in this part that include *Afzelia quanzensis*, *Hymenaea verrucosa*, *Combretum schumannii* and *Manilkara sansibarensis* and the *cycad Encephalartos hildebrandtii* (Forest Management Plan Team, 2002). The second dominant vegetation is *Bracbystegia* Forest which is an open forest spanning about 7700 hectares that primarily has *Brachystegia spiciformis* on dry and infertile sands in the center of the forest (Forest Management Plan Team, 2002). Thirdly, there is the *Cynometra* Forest which is a “dense forest or thicket on the north-west side spanning about 23,500 ha on the red Magarini sands towards the western side of the forest. It is dominated by trees of *Cynometra webberi* and *Manilkara sulcata*, and the euphorbia species *Euphorbia candelabrum*" (Forest Management Plan Team, 2002). There are also a number of species that are near threatened or vulnerable due to their increased use for resources (Habel et al, 2017). Many tree species are harvested for wood carvings, charcoal, firewood, timber and building supplies (Table 1).

Table 1. The three dominant vegetation species in Arabuko Sokoke Forest, *Cymometer*, *Branchiostegal*, and mixed, with their degree of endangerment and type of uses such as carving, timber, firewood, charcoal, and poles.

Vegetation Type	**Species**	**IUCN Category**	**Uses**
Cynometra forest	*Brachylaena huillensis* *Cynometra webberi* *Euphorbia candelabrum* *Manilkara sulcate* *Oldfieldia somalensis*	Near threatened. Vulnerable Not listed Not listed Not listed	Carving, timber, charcoal, poles Carving Traditional use Firewood, timber, carving Not described
Brachystegia forest	*Brachystegia spiciformis*	Not listed	Firewood, charcoal, timber
Mixed forest	*Afzelia quanzensis* *Combretum schumannii* *Drypetes reticulata* *Encephalartos hildbrandtii*	Not listed Not listed Not listed Near threatened	Timber, poles. Firewood, charcoal, timber, carving Charcoal, poles Ornamental purposes

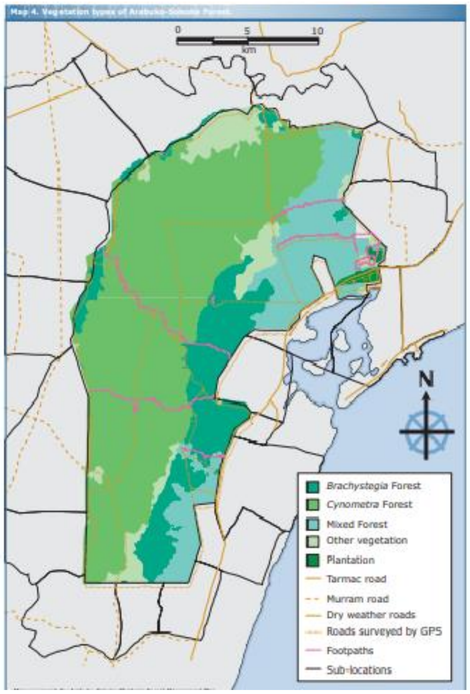


Figure 2. Displaying the different vegetation types of Arabuko Sokoke National Reserve. This map was taken from the Arabuko Management Plan for 2002-2027.

3.2 Data Preparation

Moderate Resolution Imaging Spectroradiometer (MODIS) is an important tool aboard the Terra and Aqua satellites that predicts global change over time (NASA, 2021). The MODIS vegetation indices provide spatial and temporal data to compare vegetation greenness, leaf area, chlorophyll and canopy structure (NASA, 2021). The two vegetation indices that are derived in the MODIS imaging is the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). These data sets can help portray vegetation quality and processes (NASA, 2021).

In this study, eMODIS was used to analyze the vegetation dynamics and was based on the Normalized Difference Vegetation Index (NDVI). The data resolution was 250m. NDVI is calculated using red and near-infrared wavelengths of light that are reflected and captured by the satellite. Chlorophyll will absorb red light, while the mesophyll structure of a leaf will scatter reflected near-infrared light. Therefore, if the proportion of reflected near-infrared light is greater than red light captured this represents a signal of vegetation. NDVI values increase from 0 to 1 as the amount of vegetation increases, whilst lower values indicate an absence of vegetation. In eMODIS data, band 2 represents the near-infrared reflectance (871–876 nm) and band 1 represents the red reflectance (620–670 nm). The NDVI was calculated as:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (1)$$

A maximum value composite (MVC) method was applied to get the monthly NDVI data from decadal data this was to reduce the atmospheric effects of clouds and aerosol. The annual and seasonal NDVI time-series were calculated by averaging the monthly and seasonal data. All calculations were done using R script (R Core Team, 2021 –Annex 1). The data was downloaded from United States Geological Survey Famine Early Warning Systems Network (USGS FEWS NET) Data Portal based at Earth Resources Observation and Science Center (https://earlywarning.usgs.gov/fews/datadownloads/East%20Africa/eMODIS%20NDVI%20C6).

By using the monthly mean NDVI from 2003-2020, data was extracted in R Studio to identify a time series for the forest that includes a trend-cycle component, seasonal component, and a remainder component (Figure 3). The analysis indicated the forest has 4 seasons. Long dry season includes December-January-February-March (DJFM), long rainy wet season – April-May-June-July (AMJJ), short dry season – August-September (AS) and short rainy season October-November (ON). After the seasons were defined for the forest, the MODIS images were simplified for the analysis to follow (Figure 5).

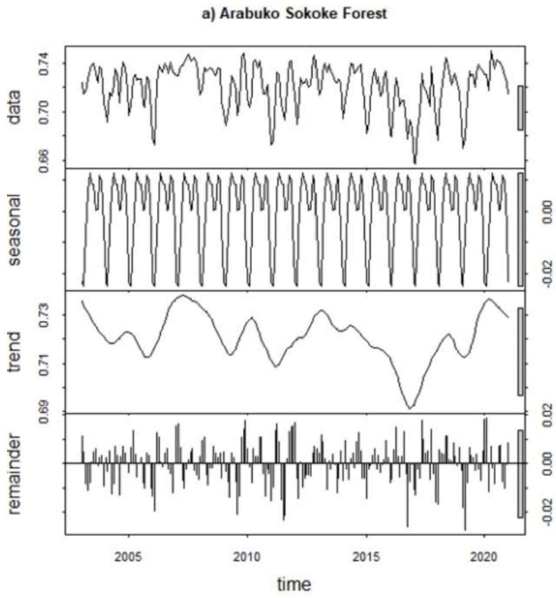


Figure 3. The time series using the mean NDVI data to determine the 4 seasons. If the seasonal, trend and remainder are added together, they equal the data. Figure courtesy of Dr. Mohammed Said.

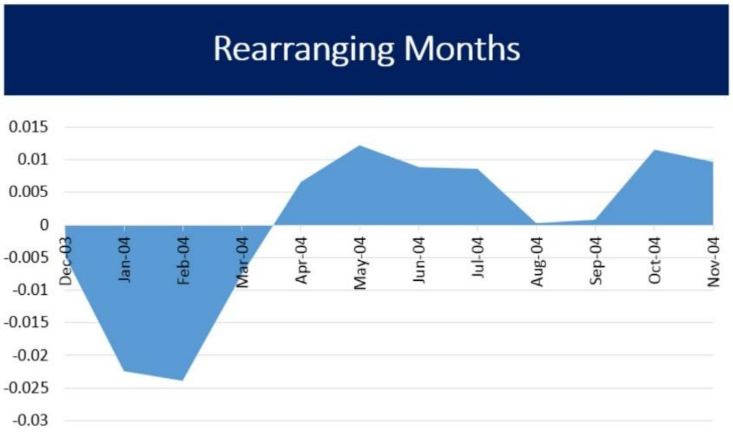


Figure 4. Visually displaying the trend to identify the 4 seasons used in this study.

3.3 Data Analysis

The vegetation condition index (VCI) was used to analyze the forest phenology. The VCI is usually represented as a percentage and is a "pixel-wise normalization of VI that is useful for making relative assessments of changes in the VI signal by filtering out the contribution of local geographic resources to the spatial variability of VI" (Jiao et al., 2016). The VCI is calculated using the formula:

(2)

$$VCI_{ijk} = \frac{VI_{ijk} - VI_{i,min}}{VI_{i,max} - VI_{i,min}}$$

In this computation, "VI_{ijk}represents the monthly VI for pixel *i* in month j for year k, and $VI_{i,max}$ and $VI_{i,min}$ denote the multiyear maximum and minimum VI, respectively, for pixel *i* in month *j*" (Jiao et al, 2016). In this study, the VCI was computed based on the formula wherein VI is replaced by NDVI (Figure 5-Annex 2).

3.4 Visualization

The 90 images from every year and 4 seasons of VCI data from 2003-2020 were placed into QGIS 3.18. The Arabuko Sokoke Forest boundaries were received as a shapefile from the Friends of Arabuko Sokoke. A discrete color scheme was defined with 4 classes to describe the VCI trends from 0 to 1. Although VCI is expressed in a percentage by multiplying by 100, on the scale, 0 is poor vegetation condition and 1 is excellent vegetation condition. These maps were used to identify trends annually in the forest as well as the other 4 seasons.

3.5 Relationship between NDVI and climatic drivers

Regression is useful in assessing the strength of the relationship between variables. Regression analysis was used to analyze whether NDVI was related or driven by rainfall and temperature. Regression analysis assumes a normal distribution of the residuals and constant variance of the error component. The relationship between the NDVI and climatic variables were tested to find out if the relationship were linear or quadratic or inverse or logarithmic. The choice of the model was based on the corrected Akaike Information Criterion (AICc). In this study the best model or fit was based on a 3-month lag (3 months moving average) of both rainfall and temperature as NDVI values were based on past accumulated rainfall or temperature (Dr. Mohammed Said, 2021).

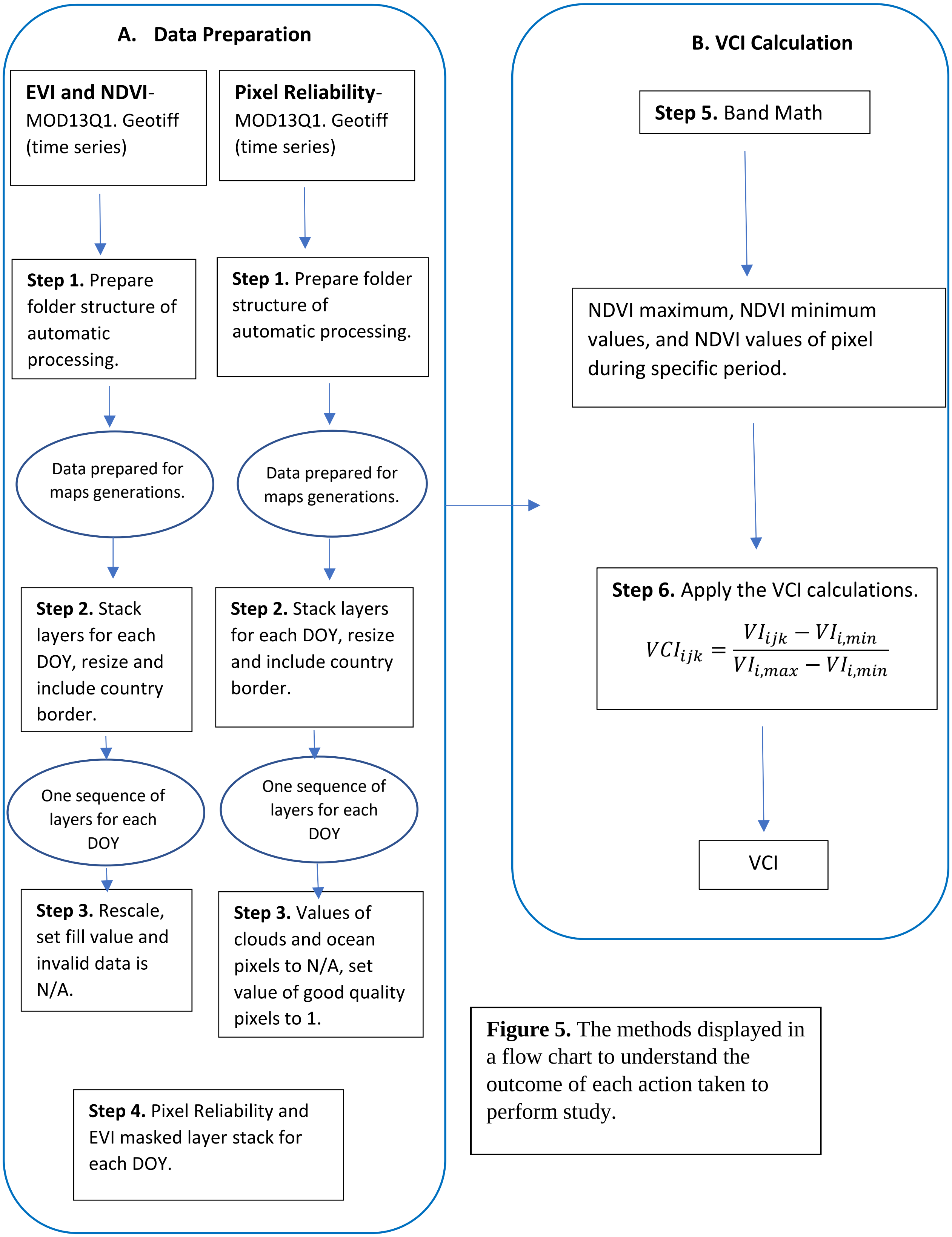
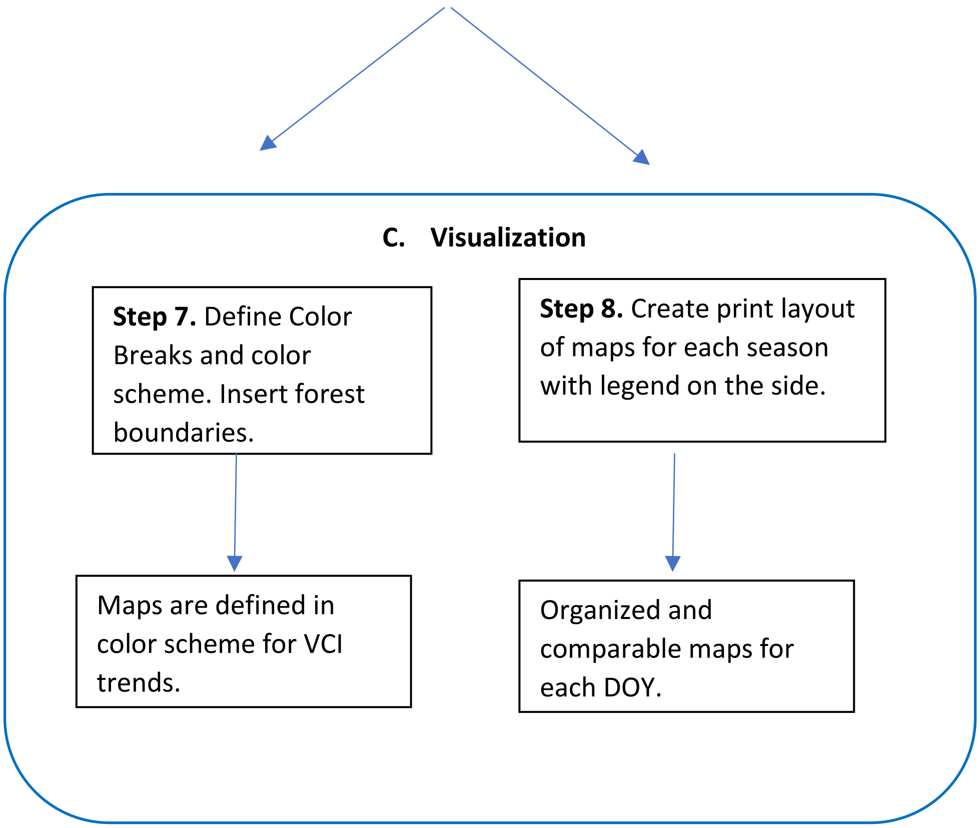


Figure 5. The methods displayed in a flow chart to understand the outcome of each action taken to perform study.


C. Visualization
Step 7. Define Color Breaks and color scheme. Insert forest boundaries.
Step 8. Create print layout of maps for each season with legend on the side.
Maps are defined in color scheme for VCI trends.
Organized and comparable maps for each DOY.

CHAPTER FOUR

4.0 RESULTS

There were 90 images that were mapped in QGIS displaying the boundaries of Arabuko Sokoke Forest. The vegetation condition index grades ranged from 0 to 1. If an area ranged from 0-0.30 the vegetation is characterized to be in a severe drought, 0.30-0.50 is a moderate drought, 0.50-0.70 is a slight drought and above 0.70 is normal vegetation and healthy vegetation (Liang et al, 2017). The maps were divided into 5 distinct seasons.

4.1 Annual

There were 18 maps created annually from 2003 to 2020 by MODIS imaging (Figure 6). In 2003, there was healthy vegetation on the east border of Arabuko Sokoke with VCI grades ranging from 0.70 to 1.0. However, there is some lower grades between 0.30 and 0.70 in the southern half of the park and inside the eastern borders. In 2004, 2005, and 2006, the maps were fairly patchy, with severe droughts and VCI grades of 0.0 to 0.70, in the north west corner stretching south into the forest boundaries. In 2007, there was high VCI in most areas with grades between 0.70 and 1.0. In 2008, VCI grades ranged from 0.0-0.50 in the north west areas adjacent to the forest that extended through the center of the forest. In 2009, 2010, 2011, there appeared to be severe droughts, with many patches of land having VCI grades of 0.0 to 0.30 in the southern half of the park and along the western and northern sections of the forest and adjacent lands. In 2012, 2013, 2014, and 2015, there were patches of low VCI, between 0.0 and 0.70, in the southern half of the park and the north west adjacent lands outside the forest. However, in 2013, there was healthy vegetation with VCI grades above 0.70, in the north east section of the forest within the boundaries. On the other hand, between the years of 2016 and 2017, most of the lands within the forest boundaries and the adjacent areas were in a severe drought, with extremely low VCI grades between 0.0 and 0.30 or 0.30 and 0.50. The maps created were almost completely red and orange. In all the maps, there tended to be lower VCI values ranging between 0.0-0.70 in the north west corner and in southern portions of the forest ecosystem. In 2018 and 2019, VCI grades were low, between 0.0 and 0.50, especially along the southern borders of the forest and in the north west surrounding lands. Lastly in 2020, there was normal vegetation which can be defined as VCI grades above 0.70. However, it is important to address the section of disturbance along the south east border of the forest, with lower VCI grades between 0.30 to 0.70.

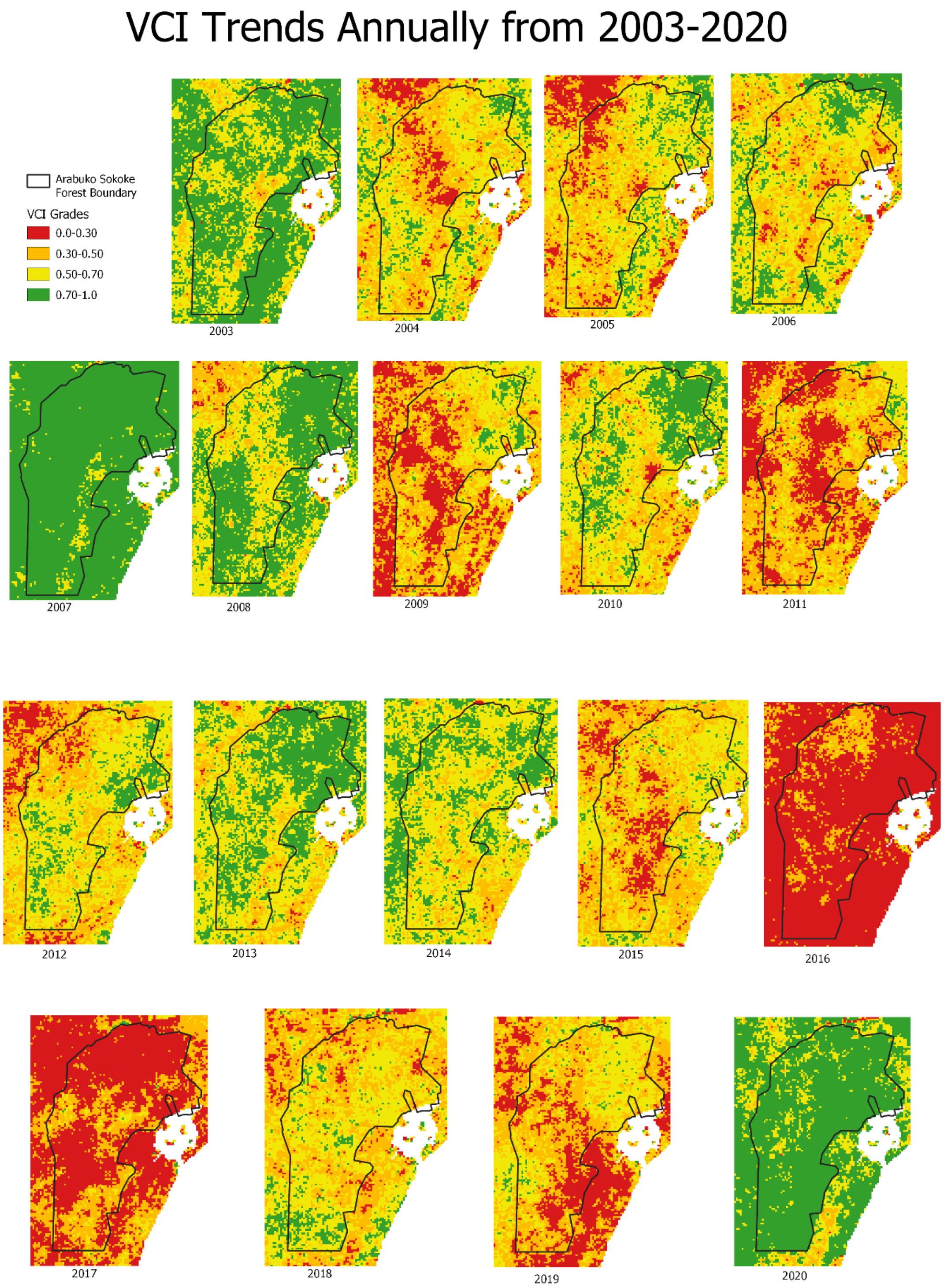


Figure 6. Annual VCI data for 2003-2020. VCI grades range from 0.0-1.0 with 0 being poor vegetation or in a severe drought and 1 being very healthy condition.

4.1.1December, January, February and March

There are 18 maps created for the years between 2003 to 2020 that established the VCI trends for December, January, February, and March (Figure 7). In 2003, the VCI grades were fairly normal, being above 0.70 in the forest boundaries. However, there is a small patch in the south of Arabuko Sokoke with low VCI grades of 0.0 to 0.50. In the adjacent lands on the south west boundaries of the forest, there was a slight drought with VCI grades of 0.50 to 0.70. In 2004 and 2005, there are disturbances to the north west with VCI grades between 0.0 to 0.30 that extend into the forest boundaries. In 2006, the majority of the vegetation fell into poor quality and had an extremely low VCI ranging from 0.0 to 3.0. However, in 2007, there was a transition to healthy vegetation, VCI grades above 0.70, within the forest and adjacent lands. In 2008, 2009, and 2010, there is fairly normal vegetation with VCI grades above 0.70 in the forest boundaries, but disturbances with VCI grades of 0.30 to 0.70 through the center of Arabuko Sokoke. In 2011, there was low VCI grades, 0.0 to 0.30, in the southern half of the forest and the north west area outside the boundaries. This extended through the northern section of the forest. There were small patches of healthy vegetation with VCI grades above 0.70 in the norther half of Arabuko Sokoke. In 2012, 2013 and 2014, almost all the healthy vegetation, above 0.70, is located only within the Arabuko Sokoke borders. The adjacent lands have low VCI grades, 0.0 to 0.70, along the forest borders. There are interesting patterns in 2015, where there is a severe drought, with VCI grades from 0.0 to 0.30, inside the forest along the edge of the east border. For 2016, there was poor vegetation condition, with VCI grades of 0.0 to 0.30 in the northern half of the forest near the main entrance. However, 2017 is one of the most notable since most of the vegetation is in a severe condition, with the VCI grades below 0.30. In 2018 and 2019, there was fairly patchy, with poor vegetation ranging between 0.0 and 0.50, in the south and north west lands next to the forest, extending into the forest lands. In 2019, there was one healthy forest patch in Arabuko Sokoke border on the south west side of the forest. Lastly, in 2020, there was healthy vegetation throughout the entire map, with land inside the forest and the surrounding areas with VCI grades above 0.70.

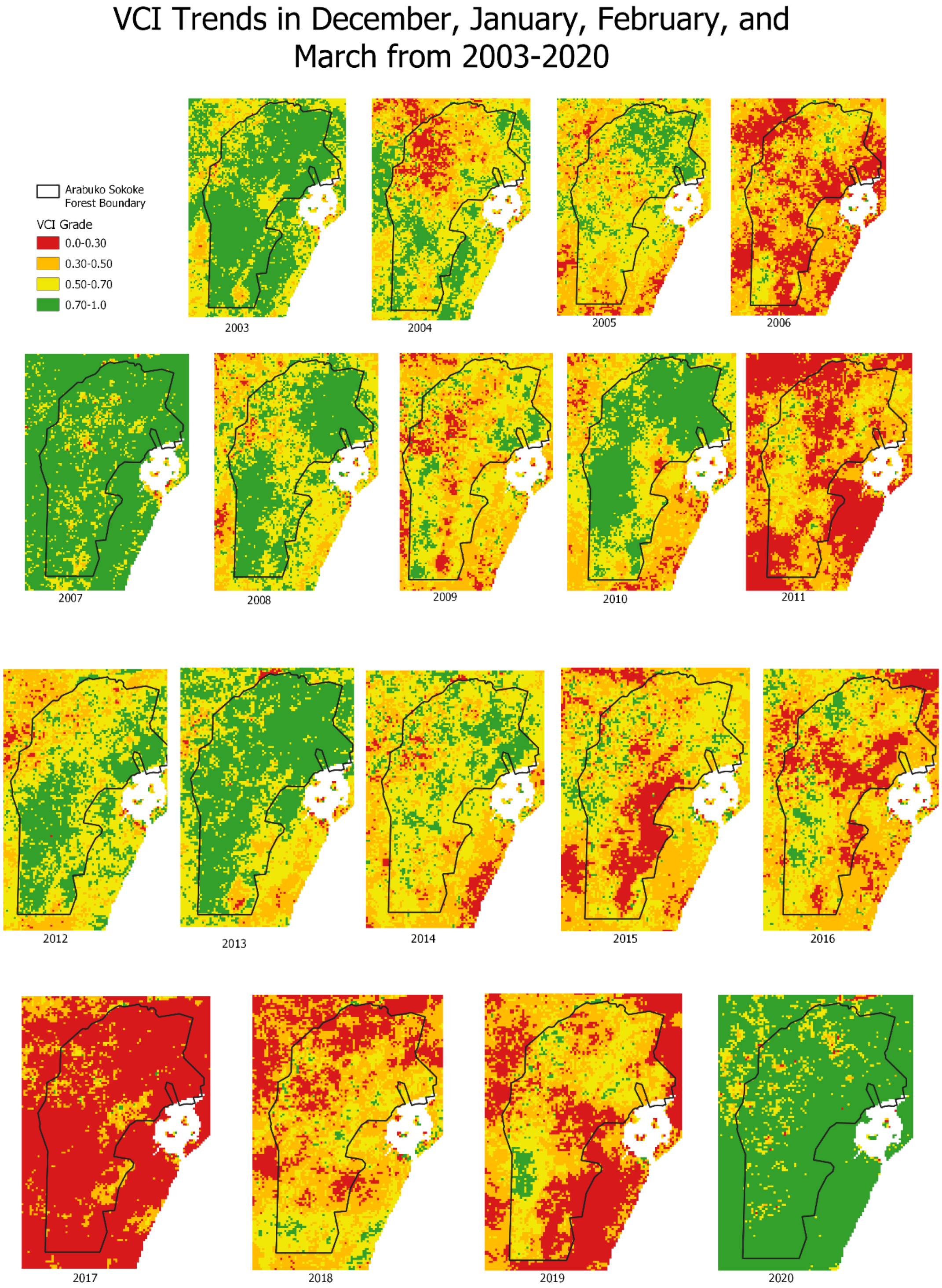
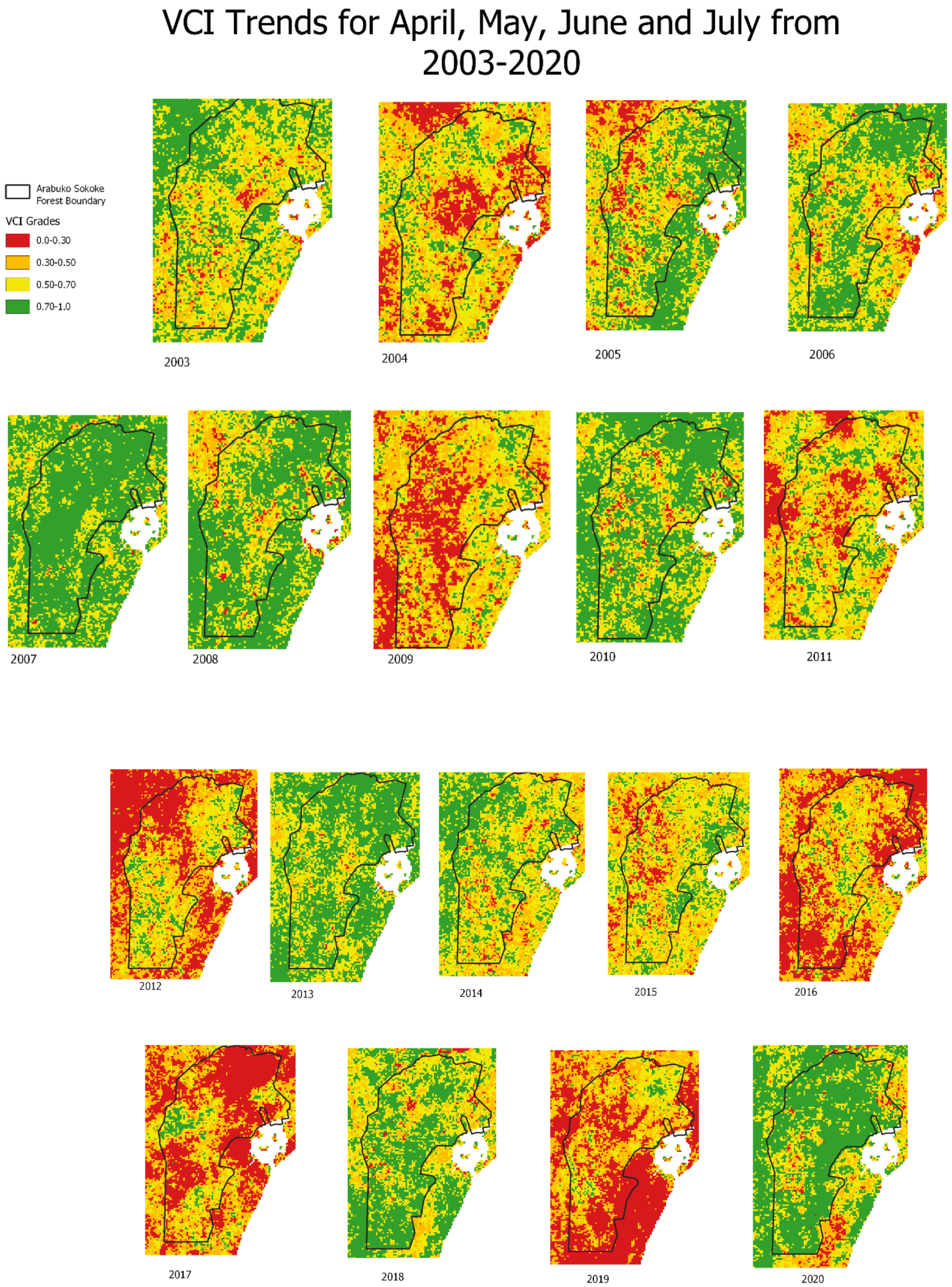


Figure 7. VCI Trends mapped for December, January, February and March for 2003-2020. VCI grades range from 0.0-1.0 with 0 being poor vegetation or in a severe drought and 1 being very healthy condition.

4.1.2 April, May, June, July

There were 18 maps produced for the months of April, May, June and July from 2003 to 2020 (Figure 8). In 2003, 2004, 2005, and 2006, there are significantly patchy areas. In 2003, there was healthy vegetation in the north west areas outside the forest, VCI grades were above 0.70. However, in the following years of 2004 and 2005, there was disturbances and droughts in this area, having grades of 0.0 to 0.30. In 2007 and 2008, there was fairly healthy vegetation across the land, with VCI grades above 0.70. For 2009, there was severe drought, with a low VCI of 0.0 to 0.30, throughout the center of the forest that spreads south east. In 2010, there is high VCI grades above 0.70, with small sections throughout the forest with low VCI grades of 0.0 to 0.70. For 2011 and 2012, there is low VCI in the north west lands that partially spread into Arabuko Sokoke. From 2013, 2014 and 2015, there is the gradual loss of healthy vegetation, with the VCI ranging from 0.70 to 1.0 in 2013 and falling to 0.0 to 0.50 in 2015. In 2016, 2017, and 2019, there are severe droughts in the north east lands and southern half of the park with VCI grades of 0.0 to 0.50. In 2018 and 2020, the normal or healthy vegetation is located within the forest borders. However, there is a section of adjacent land in the south east that has moderate and severe droughts with a VCI value of 0.0 to 0.50.



VCI Trends for April, May, June and July from 2003-2020

Figure 8. VCI trends mapped for the months of April, May, June and July from 2003-2020. VCI grades range from 0.0-1.0 with 0 being poor vegetation or in a severe drought and 1 being very healthy condition.

4.1.3 August and September

There were 18 maps created for the months of August and September between 2003 and 2020 (Figure 9). In 2003, the map was fairly patchy with VCI values above 0.70, but there was a disturbed patch ranging from 0.0 to 0.50 on the edge of the north east border in Arabuko Sokoke. For 2004 and 2005, most of land received VCI values of 0.0 to 0.70 with very little healthy vegetation. In 2006, 2007, 2008 and 2010, the healthy vegetation, with values over 0.70, covered the majority of the maps with occasion lower VCI in the southern half of the forest. However, in 2009 and 2011 there were severe droughts with VCI values below 0.30 encompassing most of the maps. Between 2012 and 2015, most of the land in Arabuko Sokoke and adjacent were in a slight drought ranging from 0.50 to 0.70 with patches above 0.70 within Arabuko boundaries. In 2016 and 2017, vegetation was poor having values of 0.0 to 0.30 in the north east and north west lands as well as the southern half of the forest. From 2018 to 2020, there was a gradual increase of healthy vegetation with VCI above 0.70 in Arabuko Sokoke borders. By 2020, there was only healthy vegetation condition within the forest borders. There was a severe drought, with a VCI grade 0.0 to 0.30, on the southern edge of Arabuko Sokoke outside the boundaries.

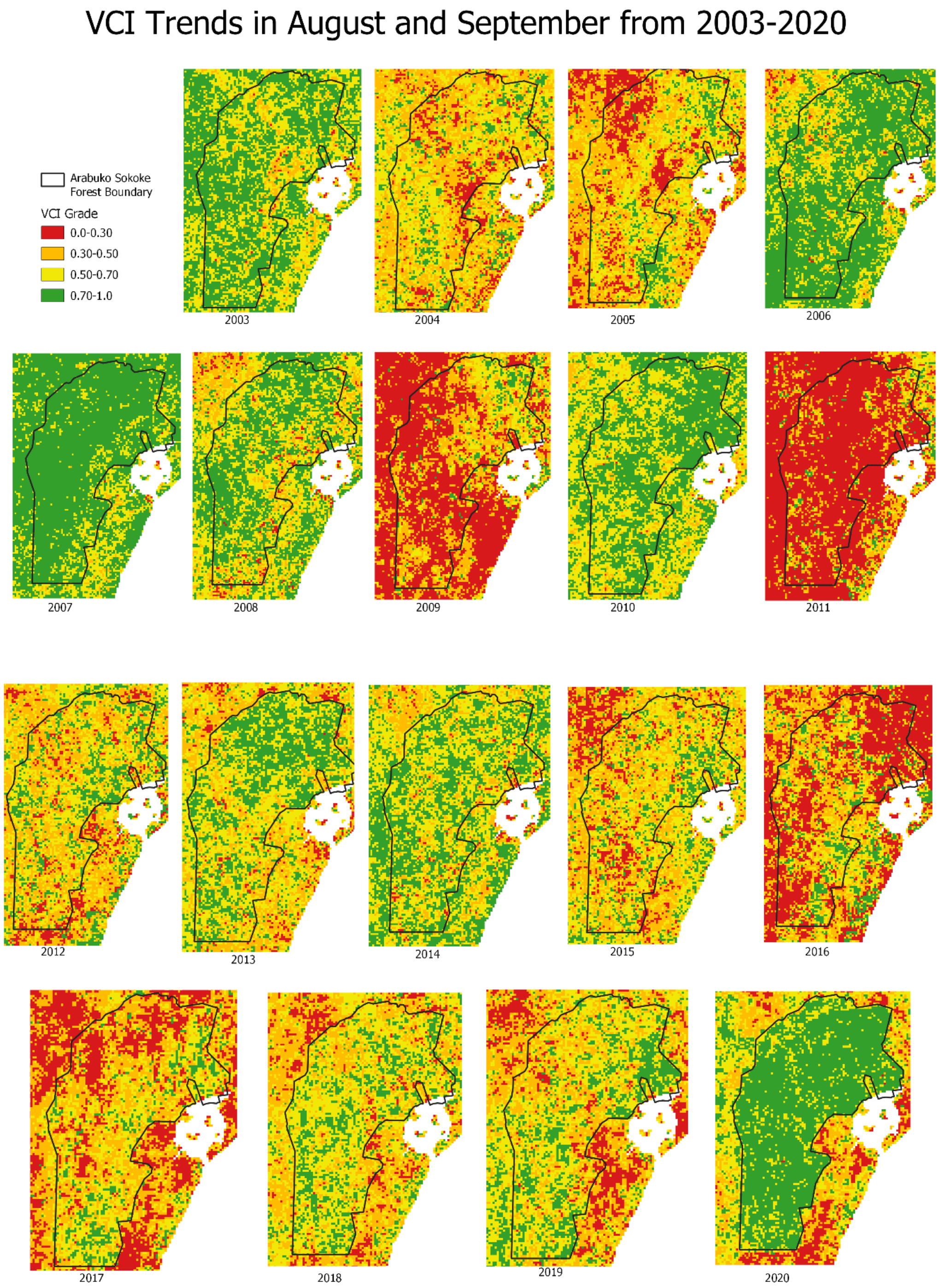


Figure 9. VCI trends for the months of August and September from 2003-2020. VCI grades range from 0.0-1.0 with 0 being poor vegetation or in a severe drought and 1 being very healthy condition.

4.1.4 October and November

Lastly, there were 18 images projected for October and November between the years of 2003 and 2020 (Figure 10). All the maps had fairly healthy vegetation for the last 18 years during October and November. In 2003 and 2004, there was healthy vegetation with VCI values above 0.70 in the southern half and in the borders of Arabuko Sokoke in the north east. In 2005, there appeared to be a drought, with a VCI grade of 0.0 to 0.30, in the north west area outside the forest. However, in 2006, 2007, 2008 and 2009, VCI trends did not fluctuate and remained in a healthy condition, with grades above 0.70. This transitioned in 2010, where there were severe droughts in the north west areas, center of the forest and southern edges of Arabuko, with VCI values between 0.0 and 0.30. From 2011, 2012, 2013, and 2014, the majority of vegetation was healthy, but it was patchy throughout the study area, having VCI values above 0.70. In 2015, 2017 and 2018, the lands were in a slight drought, with VCI ranging from 0.30 to 0.70 in the borders and adjacent. In 2016, there was only poor vegetation conditions with the entire map including VCI values ranging only between 0.0 and 0.30. Lastly in 2019 and 2020, there were high VCI grades that reached only within the Arabuko Sokoke borders. The adjacent lands in 2020 ranged between 0.50-0.70, especially on the edges of the forest boundaries.

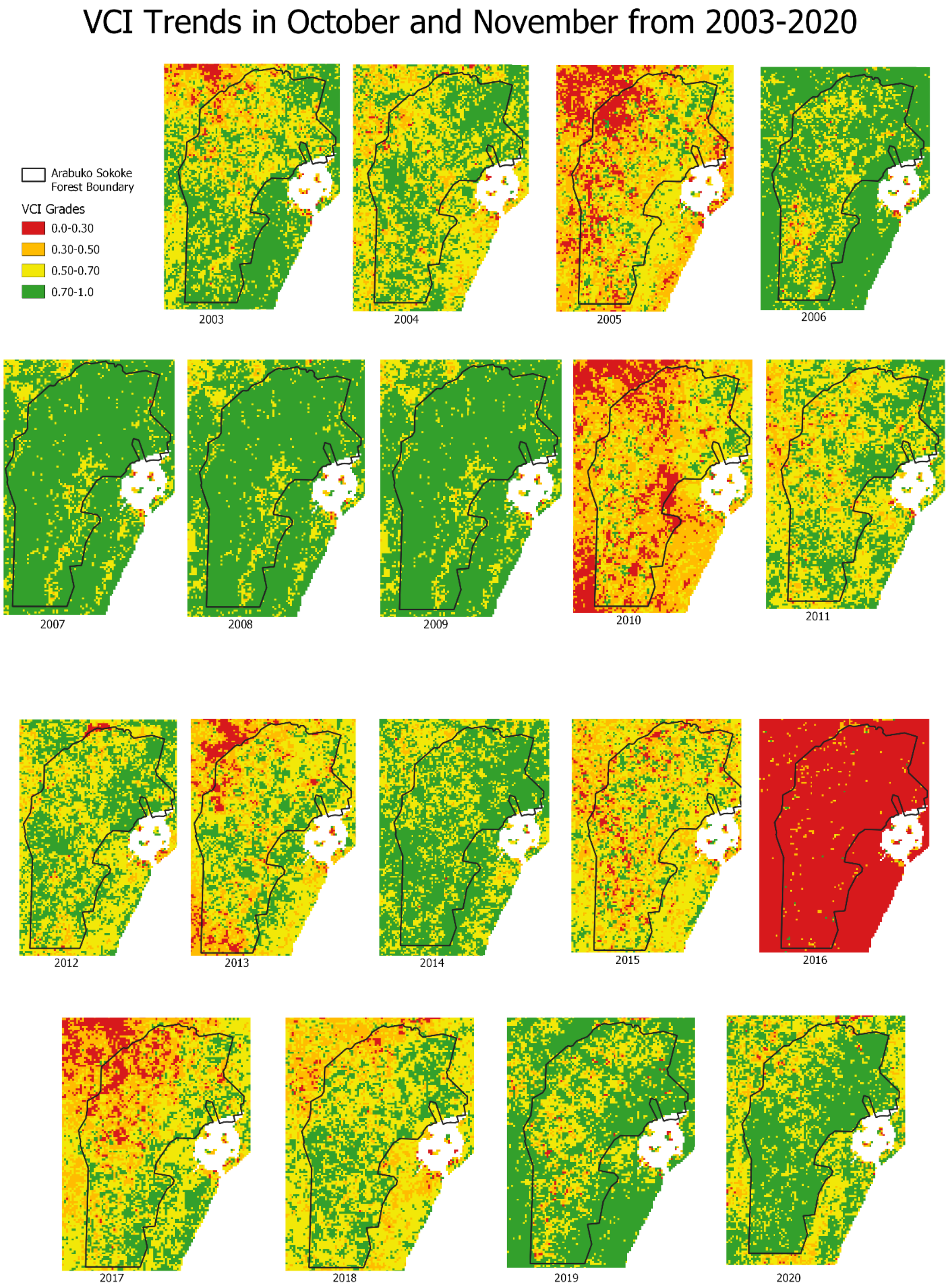


Figure 10. VCI trends for the months of October and November from 2003-2020. VCI grades range from 0.0-1.0 with 0 being poor vegetation or in a severe drought and 1 being very healthy condition.

CHAPTER FIVE

5.0 DISCUSSION

The purpose of this study was aimed to assess the spatial-temporal change in forest phenology from 2003 to 2020 in Arabuko Sokoke Forest using the remotely sensed Vegetation Condition Index (VCI). The specific objectives of the study, which included mapping the spatial-temporal changes as well as analyzing them, were accomplished. The hypothesis of my study stated that there would be immense vegetation phenological change in the last 20 years, especially between the years of 2015 to 2020. My hypothesis was supported to an extent, but it would be greater if there was a more in-depth analysis. The finding of this research indicates that the vegetation phenology has always been changing over time that depends on the distinct season or year. The distinct driver may not have been identified with VCI but can be investigated further. Based on NDVI patterns, the SVI, rainfall and temperature, there may have been climatic drivers at play in causing the vegetation change. Although there has been previous studies on vegetation loss, biodiversity loss, and change in certain types of vegetation, my study identifies the change in forest phenology over the last 18 years. Based on the results of the study, there are works of others that can support the trends found in the 90 maps for the 4 dry and wet seasons of Arabuko Sokoke.

5.1 Population Growth and Environmental Degradation

As it was previously investigated, there are around 50 villages adjacent to Arabuko Sokoke Forest which use its resources daily. However, compared to the entirety of the coastal region, the Arabuko Sokoke ecosystem has the highest density of individuals (Habel et al. 2017). According to the Government of Kenya (2013), in the surrounding counties of Kilifi and Malindi county, there was a growth rate of 3.05% between 2015 and 2017. For example, the years 2016 and 2017 only had low VCI values, indicating a severe drought (Figure 6). This was mirrored in other seasons as well. In 2017 for December, January, February, and March, there was a severe drought (Figure 7). In 2016 during October and November, there was a severe drought that impacted the ecosystem with poor VCI grades (Figure 10). With many maps displaying poor VCI while there is a large growth rate, it may be probable that the population growth impacts ASF through intensified use of the forest's natural resources (Shurmann et al, 2020). However, there would need to be additional research to establish correlations.

Since there is vast population growth in this region, there is a need for more agriculture and land competition. From 1954 to 2017, large portions of "shrubland and bushland were converted into agricultural land (51.2% and 50.7% respectively). This has increased the homogenization of the landscape" (Shurmann et al, 2020). While this indicates that the land is constantly evolving for population, landscape homogenization can be detrimental to the environment. Landscape heterogeneity has long been considered a key determinant of biodiversity, reflect species traits and land cover (Katayama et al., 2014). Similarly, if land use is not diversified, land deterioration may be present. In Kilifi County, effects of environmental degradation are being witnessed throughout the area. The over exploitation of forest and other non-renewable resources within the area are being escalated with the high population density as well (Government of Kenya, 2013). Additionally, the “indiscriminate felling of trees in gazetted and non-gazetted forests has led to environmental degradation leading to drought in most parts of the county” (Government of Kenya, 2013). Therefore, the Vegetation Condition Index (VCI) that was mapped in the 90 images of Arabuko Sokoke helped determined when there were serve droughts in the area during certain times of the year, especially between the years of 2016 and 2017 (Figure 6).

It is important to acknowledge that there is some disturbance in the southern half of the Arabuko Sokoke Forest. For instance, in 2020 during the months of August and September, the forest is almost completely normal vegetation condition. However, outside of the forest boundaries there is poor VCI in the south (Figure 9). According to a Forest Cover Survey of Arabuko Sokoke by A Rocha Kenya, a majority of the cutting has “occurred in the southern half of the forest. This perhaps reflects the greater distance from the main headquarters for the Forest Management and a possibly different patrolling regime to the northern section. Significant numbers of cut stems were also found near Jilore and Arabuko though these had been cut over a year before mid-2006” (Waters, Jackson and Jackson, 2007). Not only is it crucial to use the research provided by A Rocha Kenya, but also the VCI observes the current NDVI and relates it to the same period over time. This can help identify areas where drought may occur on multiple occasion due to over exploitation of resources. Therefore, it is possible for forest managers to focus on patrolling certain areas based on the amount of logging activity to reduce illegal cutting which also may cause droughts and barren land as seen with VCI (Waters et al. 2007).

Similarly, on multiple occasions, there are lower VCI grades on the edges of the forest. It can primarily be seen in adjacent lands to the forest. For instance, there are clear edge effects during 2019 and 2020 (Figure 6 and Figure 9). In December, January, February and March 2008, 2010, and 2013 also had clearly degrading edges (Figure 7). According to Waters et al (2007), there are a couple options to why this may take place. As it was stated previously, the forest is made up of three forest types: *Brachystegia*, *Cynometra* and Mixed (Figure 2). Therefore, one alternative infers that specific trees in the *Cynometra* forest have been targeted in the past for logging (Waters et al, 2007). This action appears to have decreased since the number of high value trees has been reduced, specifically *B. huillensis* (Waters et al, 2007). Since higher quality trees have been diminished, the easier accessed ones, such as the ones near the edge, will be used more frequently (Waters et al, 2007). In terms of primary accounts, I witnessed individuals that crossed under the border fence from adjacent establishments. While I do not know their exact activities, it was most likely to a potential subsistence zone. In comparison, I observed logging and construction happening on the border of the forest along the main highway on the east border. According to the Arabuko Sokoke Forest Management Plan (2002), the forest areas lying close to villages are most heavily used by villagers for their subsistence fore product needs. With the accessibility of such resources, there is widespread destruction of the environment through uncontrolled cutting of trees within Mombasa, Malindi, Kilifi and Mtwapa (Government of

Kenya, 2013). These areas are major producers of charcoal that contribute to the economy and daily lives of the individuals of the coastal region (Government of Kenya, 2013). Although VCI does not determine the type of cause for the poor vegetation condition, these maps identify areas that researchers should focus on within the forest or in the surroundings to reduce the chances for severe droughts and poor vegetation quality in the future.

5.2 NDVI, Rainfall, Temperature and SVI

While there may have been direct human effects on Arabuko Sokoke, there are also natural drivers of phenological change. The following trends identified between NDVI, rainfall and temperature add evidence to support the 90 VCI images for the last 18 years. Between 2001 and 2020, there appeared to be high rainfall in 2007, but reaching record lows between 2016 and 2017 (Figure 11). The healthy VCI grades, above 0.70, in 2007 and the poor VCI grades, below 0.30, in 2016 and 2017 mirror the results of this diagram (Figure 6). These rainfall trends were placed into a regression in relation to the NDVI of Arabuko Sokoke. Regressions are useful to assess the strength of a relationship between different variables. As stated previously, the regressions were performed to support evidence if the phenological change was due to rainfall or temperature based on a 3-month lag. For the NDVI and rainfall, it was seen that there was a linear relationship between the two factors, but it was not strong statistically (Figure 12). The R squared for this regression was 0.1151, indicating a lower significance (Figure 12).

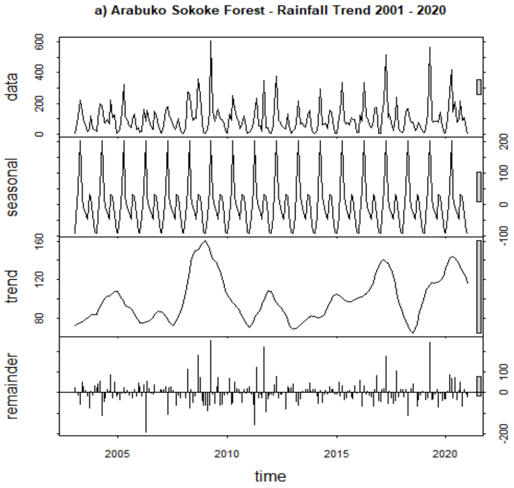


Figure 11. This diagram displays the trends for rainfall in Arabuko Sokoke Forest from 2001 to 2020. It is dissected into 4 sections, the data, seasonal, trend and remainder.

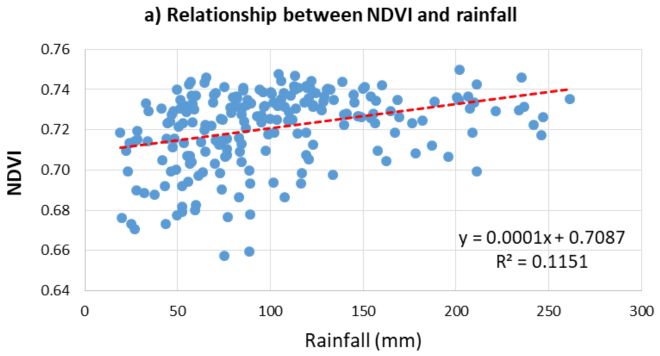


Figure 12. This graph displays a regression of the relationship between the NDVI and rainfall. There is a linear relationship, but not a strong significance between the two factors with the R squared being 0.1151.

This process was repeated for the temperatures between 2001 and 2016. Previous to 2010, there were consistent low temperatures, but it spiked around 2010 from 34.0 degrees Celsius to 34.8 degrees Celsius. This trend remained high until 2016 (Figure 13). Similarly, the temperature was placed into a regression in relation to the NDVI of Arabuko Sokoke (Figure 14). There appeared to be a stronger relationship between these two factors more than the precipitation. There was a quadratic relationship between NDVI and temperature (Figure 14). The R squared was 0.3141 indicating a more significant relationship as well. As the NDVI increased, the temperature also grew. However, as the NDVI decreased, the temperature continued to rise (Figure 14). These trends in rainfall and temperature can further help identify which years were stressed the most in the last 18 years. The trends and regressions also help establish if precipitation and temperature are drivers of the change over time.

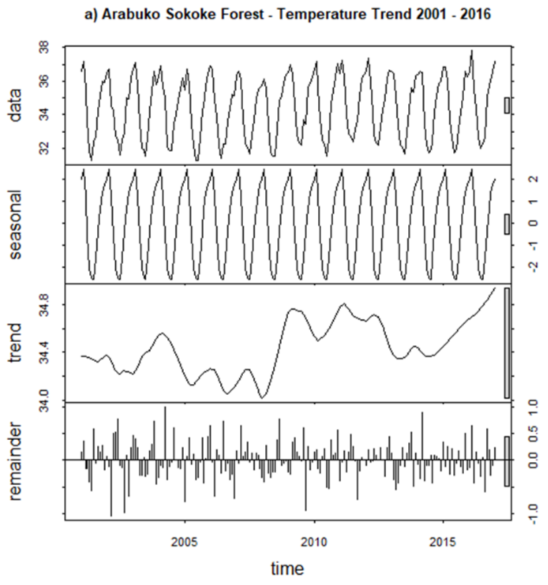


Figure 13. This diagram shows the temperature trends for Arabuko Sokoke Forest from 2001 to 2016. It is divided into the data, seasonal, trends, and remainder.

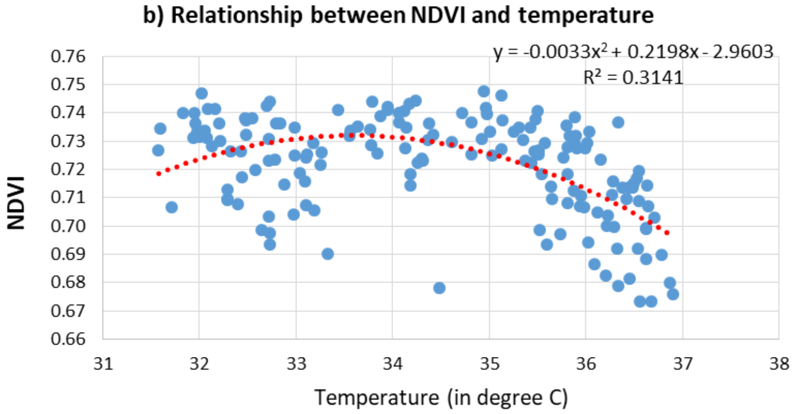


Figure 14. This graph is a regression of the relationship between NDVI and temperature. As it can be seen, there is a quadratic relationship and more significance between the two factors with the R squared being 0.3141.

In order to further this understanding, the standard vegetation index (SVI) was plotted. Since the state of vegetation is determined by climatic conditions, the standard vegetation index can be used to assess vegetation condition trends and monitor certain areas over time. The SVI ranges from -2 to 2. -2 indicates extremely dry conditions while 2 is extremely wet (Figure 15). The SVI helps support the visualization of vegetation health and greenness based on the NDVI. In the SVI, it was found that January, February, March and April were the months under severe stress with extremely or moderately dry conditions (Figure 15). This poor vegetation was mirrored in the VCI maps for this season (Figure 7). However, from 2014 to 2019 during the months of January, February, March and April, there was a severely stressed period (Figure 15). This was able to be seen in the VCI maps for DJFM between 2015 and 2019 (Figure 7). In the years of 2016 and 2017, it was almost all dry except during May and June, where vegetation was considered to be normal (Figure 15). These trends were reciprocated in the annual VCI images where VCI grades were low (Figure 6). In the VCI maps for AMJJ, there were less severe droughts in the forest (Figure 8).

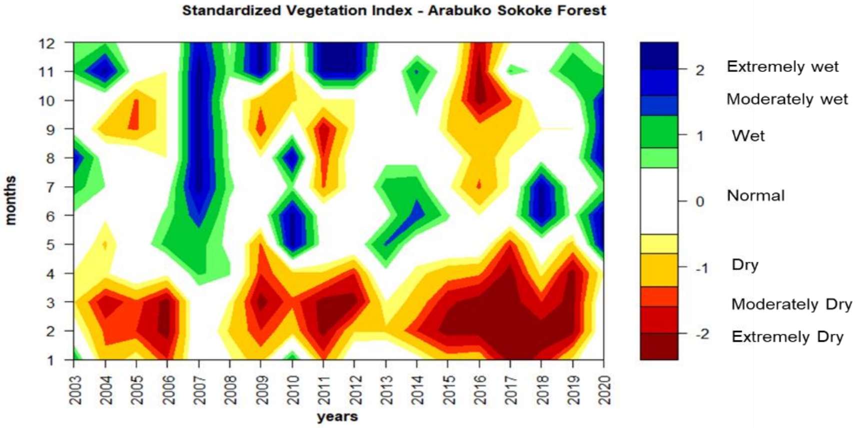


Figure 15. This diagram is the standardized vegetation index for the Arabuko Sokoke Data. In this diagram, -2 is extremely dry, while 2 is extremely wet. There appears to be a high stress period from January to March in 2014 through 2019.

It is also important to address that in 2007, there was wet, moderately and extremely wet conditions with little stress to the vegetation (Figure 15). This was mirrored in the VCI annual trends where the values were above 0.70 (Figure 6). In addition, the trends for temperature, rainfall and the standard vegetation index can help not only support the trends found in the VCI images, but also identify possible drivers of the changing condition over time.

5.3 Improving Vegetation Quality

In order to reduce the chances of drought and poor vegetation in the future, policy by the Arabuko Sokoke Management Team should be reviewed. The four government departments in charge of ASF should continue to work together, along with the local communities through the Forest-Adjacent Dwellers' Association. The Arabuko-Sokoke Forum is another group that proposes to include stakeholders not represented in the management team to offer their opinions (Forest Management Team, 2002). Since one of the biggest issues for the forest includes subsistence use, there is the promotion of Agro-Forestry and aiming towards a greener economy (Government of Kenya, 2013). In Kilifi County, some of the alternative livelihoods include "bee keeping, butterfly farming, tree seedlings production, timber and extraction of herbal products…[The] promotion of tree planting by farmers and schools has been enhanced" (Government of Kenya, 2013). By having farmers plant fruit trees on their land, such as mangoes, cashew nuts, coconut and citrus, it can help minimize soil erosion and provide fuel wood for personal use (Government of Kenya, 2013). Multiple organizations like the ministry of agriculture, livestock and fisheries has been "training farmers on the best methods that ensure soil and water conservation" (Government of Kenya, 2013). Therefore, policy should be focused on assistance in the local community towards a greener economy. There should also be involvement with local schools on beautification and public works programs to display the children the importance of Arabuko Sokoke Forest and the necessity of the biodiversity as well as its natural resources for the future. The Management Team should also emphasize the need for stronger ecotourism and environmental education which can give back revenue to the community (Forest Management Team, 2002). Lastly, the need for stricter policy and patrol in all regions of the forest with more research projects is crucial for the future. By having these VCI projections, it can help identify areas that may need more patrolling or restoration due to poor vegetation quality. It is important to acknowledge that locals have relied on the forest as a source of income and believed that it was a fairly permanent livelihood. However, recently they have been noticing that there has been a drop-in butterfly populations due to droughts which decreases the quality of the vegetation in the forest (Khalif, 2011). Butterfly farming is a crucial alternative livelihood that provides an income to the local communities. With the devastating impacts of droughts and poor vegetation, it is important to implement policy that will reduce activity leading to it.

6.0 CONCLUSION AND RECOMMENDATIONS

This study can be proved useful to visually map the areas of poor vegetation over the last 18 years and to understand the possible drivers of these changes over time. It has displayed that the vegetation phenology constantly changes. It can be concluded that 2016 and 2017 were stressed years. It was established in the annual VCI trends that there was poor vegetation during these two years (Figure 6). The months that received the most stress for the condition of vegetation in Arabuko Sokoke were January, February and March (Figure 15). It also appeared there was a stress period for vegetation beginning in 2014 going to 2019 (Figure 15). This was supported by the annual VCI images as well, with the fluctuating poor vegetation (Figure 6). In 2007, there appeared to be normal vegetation and extremely wet conditions (Figure 15). This was similarly reflected within the VCI values (Figure 6). Possible drivers may not necessarily be the increasing population density or unsustainable use, but the rising temperature and lack of rainfall. Although there was a linear relationship with low significance for the rainfall and NDVI, there was a quadratic relationship with stronger significance for temperature and NDVI. With this compelling relationship between NDVI and temperature, it can be inferred that the rising temperature had a large play in the changing VCI conditions over the last 18 years, especially after 2010.

6.1 Future Research

For future studies, there should be an advancement of this analysis that quantifies the VCI in bar graphs for each image. Due to time constraints, this was not able to be performed. Additionally, there should be studies on the exact causes of phenological changes in Arabuko Sokoke Forest. This project assisted to visualize areas that may have severe droughts frequently, especially over multiple years and seasons. However, it would be practical to identify if changes were influenced by anthropogenic impacts, such as population density in the surrounding areas of Arabuko Sokoke. There should also be studies on the climate change in the region. Whether the amount of rainfall, temperature, or fires has contributed to the deteriorating vegetation condition. Similarly, the impacts of the COVID-19 pandemic has destroyed economies across the world, causing immense poverty in many locations. Therefore, it could be important to explore the VCI trends, logging, and illegal activities in relation to the COVID pandemic impact on the community. Since Arabuko Sokoke Forest is a hotspot for biodiversity with various rare and endemic species, it is crucial to examine these factors' influence on biodiversity. These future studies are vital to the survival of the forest to determine the vulnerability of plant and animal species and which season may be escalating the change.

6.2 Limitations

There were some limitations during the process of this study. The first limitation included in this study was the relocation due to COVID. Since we were not able to remain in Kenya for the rest of the program, I was not able to collect ground information from officials at Arabuko Sokoke as well as local people. Their inputs could have assisted with determining an exact cause of certain VCI grades during specific seasons or years. I was able to collect observations while driving past the boundaries and notes on a previous Arabuko Sokoke tour with all the students. Another issue that arose was the amount of time. Since we were not able to be in Kenya with our advisors, it was difficult at times to schedule meetings. Therefore, if there was more time allowed for this study, it would have been beneficial to run statistical tests for significance during certain years or seasons. Overall, this study was performed in order to identify phenological changes in Arabuko Sokoke Forest to protect its fragile and unqiue biodiversity for the future.

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7.0 ANNEXES

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \qquad (1)$$

$$VCI_{ijk} = \frac{VI_{ijk} - VI_{i,min}}{VI_{i,max} - VI_{i,min}} \qquad (2)$$