

LANDSCAPE EFFECTS ON SOIL FERTILITY ACROSS BELIZE

by

Monica Rosemarie Coe

A Professional Paper submitted in partial fulfilment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY

Bozeman, Montana

May 2022

©COPYRIGHT

by

Monica Rosemarie Coe

2022

All Rights Reserved

TABLE OF CONTENTS

ABSTRACT.....	vi
1. INTRODUCTION	1
Brief history of Maya	2
Brief history of Mennonites	4
2. METHODS	5
Geography, Physiography, and Soils of Belize.....	5
Climate	7
Background of Communities within the Study Sites	8
Study Area 1: Shipyard Community (Conservative Mennonite Community).....	8
Study Area 2: Spanish Lookout (Progressive Mennonite Community).....	9
Study Area 3: Maya Mountain North Forest Reserve (Maya Farming)	10
Land Cover Change (Forest Loss)	11
Road Density	14
Drivers to Forest Loss	14
Synthesis	14
3. RESULTS	15
Land Cover Change 1980-2020	15
Drivers to Forest Loss	17
Road Density	20
4. DISCUSSION.....	21
5. RECOMMENDATIONS FOR FUTURE WORK	27
6.CONCLUSIONS.....	27
REFERENCES CITED:.....	30
APPENDIX A: FIGURES	vii
APPENDIX B: MAPS	xi

APPENDICES

Appendix	Page
A: FIGURES	vii
B: MAPS	xi

LIST OF TABLES

Table	Page
1. Characteristics of each study site.....	7
2. Estimated decadal deforestation areas by site, 1980-2020.	15
3. Total Area and Percentage of forested areas per Study Site from 1980-2020.....	17
4. Road Density per Study Site.....	20

LIST OF FIGURES

Figure	Page
1. Map of Belize (Young, 2008).....	5
2. Cross section of the geological features throughout Belize.....	6
3. Forest VS Deforested areas within a 10 year period from 1980 to 1990	13
4. Graph showing the deforestation rate from 1980-2020 within the study sites.	16
5. Percentage of deforestation from 1980-2020.....	17
6. Tree cover loss drivers, 2000-2020 (Global Forest Watch, 2022).....	19

ABSTRACT

Globally there is an increasing rate of deforestation that leads to land deterioration, such as soil infertility. It is well established that the population is growing; therefore, there is a need to increase food security. To determine the causes of deforestation, I investigated the reasons underlying land conversion from forest to agricultural lands by answering the following questions: Was it because of accessible roads? If it is because of accessibility, how does it affect soil properties? To answer these questions, I focused on three agricultural communities: Shipyard (Conservative Mennonites), Spanish Lookout (Progressive Mennonites), and Maya Mountain North Forest Reserve (Mayas). These communities are to focus on the scale of agriculture related to each ethnicity and the rate of deforestation. I compared these parts of the country: Shipyard, Spanish Lookout, and Maya Mountain North Forest Reserve using the Geographic Information system (GIS) software, ArcPro version 2.9, to calculate the difference in deforestation by each Community using scanned maps dated 1958 by Charles Wright and datasets from secondary sources. Although the maps by Wright are outdated, the information is essential for the land use/land cover analysis. I also verified whether the forest lost was suitable (fertile) land according to Charles' Natural Vegetation and Provisional Soil Maps. The comparison helped me identify the trend in land cover change in small-scale farming, large-scale farming, and farming within a protected area in Belize. My results showed that the Shipyard and Spanish Lookout communities primarily contributed to forest loss and agriculture expansion on fertile lands. In contrast, the Mayan Community in the Maya Mountain North Forest Reserve showed much lower rates of forest loss and these soils were relatively less fertile. These results also indicated that the Mennonites practiced large-scale agriculture compared to the Maya, who practiced small-scale agriculture, based on the quantity of clearing-cutting acres of forested lands. However, the Maya Mountain North Forest Reserve's agricultural development appeared to be encroaching on non-suitable (non-fertile) lands with soils of low pH and high rainfall, which could lead to higher rates of degradation. In addition, my analysis suggested road networks were not the primary reason for deforestation since decreasing road density trends are the converse of increasing deforestation trends. Together, my results predict that if deforestation within the Maya Mountain North Forest Reserve continues to increase, then it will eventually be higher than the deforestation rates of either Shipyard or Spanish Lookout.

1. INTRODUCTION

Over the past century, human presence has caused tropical forests to disappear (Morris, 2010). Tropical forests are closed-canopy forests found in Asia, Australia, Africa, Central and South America, Mexico, and many Pacific islands (Wright, 2010). Belize had one of the highest forest covers among Central American nations until the 1960s, when large-scale agriculture replaced forestry (Young, 2008). With rapid and increasing population, development, and agriculture, Belize is experiencing a deforestation rate of 0.4%/year (Measured as the fraction of forested area converted to other uses per decade (area deforested [12800 km² as of 2020] out of the 14600 km² forested area in 2000 divided by twenty years; Ritchie & Rosser, 2021)). While Nicaragua's and Mexico's deforestation rates are 1.9%/year and 0.19%/year (Nicaragua: 19900 km² cleared [2020] out of 5400 km² forested area [2000]; Mexico: 26900 km² cleared [2020] out of 683800 km² forested area [2000]). Mexico's deforestation rate is much lower than that of Belize. However, Nicaragua's deforestation rate is higher than that of Belize.

Nevertheless, it is well known that the dynamics of land use (the anthropogenic influences on land) and land cover (the biophysical attributes of the land surface) changes are notable driving forces that are fundamental components of global environmental changes (Berry et al., 2020). Therefore, land cover change often leads to land degradation, which is the deterioration or loss of the productive capacity of the soils (GEF, 2021). Agriculture and urbanization, the principal reasons for deforestation in Belize, can lead to land degradation (erosion, soil fertility) (Meerman & Cherrington, 2005). According to land use and land cover change, the associated patterns of land conversion often lead to land degradation caused by multiple forces that include extreme weather conditions, particularly drought and human activity (agricultural expansion, urbanization, road infrastructures).

The history of Belize is no different from the history of any country; it has been essentially the history of the exploitation of its natural resources (Bushong, 1961). By

comparison, agriculture influences the generated income and expansions. Today, agricultural commodities account for ~10% of Belize's gross domestic product (O'Neill, 2022). Belize is a growing third-world country; therefore, its agricultural gross production value is reasonably lower than Nicaragua (~15%) but higher than Mexico (~3%) (Trenda, 2022). Still unknown, however, are farmer motivations for deforesting tropical forests. Is the forest cleared due to declining soil productivity under intensive agriculture or efforts to meet local or export demand for agricultural products (Moore, 2010)? Soil forms the basis of all terrestrial ecosystems and is often virtually ignored in environmental assessments (United Nations, 2017). Therefore, poor land management leads to poor soil management practices resulting in sub-optimal yields by the inefficient use of irrigation, fertilizers, livestock, and crop selection. As a result, I investigated whether the dense road network or the agricultural capacity supported by crops caused the conversion of forests. Although it cannot help us understand individual farmers' motivations for clearing forests, my investigation can improve our understanding of the reasons behind converting forests to agriculture. However, most secondary road networks were built for agricultural-related activities and are the most inadequate road system (Inter-Development Bank, 2013). Economic circumstances are highly influential, especially to the condition of these roads is influenced by economic circumstances and are graveled "feeder" roads. During the rainy season (June to November), these roads are inaccessible due to flooding, mudslide, or potholes. Detecting Land cover changes for this region required landscape GIS datasets from the United States Geological Survey (USGS; URL: <https://earthexplorer.usgs.gov>), the Biodiversity and Environmental Resource Data System of Belize (BERDS; URL: <http://www.biodiversity.bz/>), Global Forest Watch (2022; URL: <https://www.globalforestwatch.org/map/>).

Brief history of Maya

Interestingly, relatively high modern deforestation rates are likely to be 10-fold lower than the deforestation rates some experts believe might have characterized the end of the

Classical Mayan period (~900 CE), when the population of Belize might have been 4-fold greater than its current population of ~250000 (Mann, 2011). Some theories exist on why the Maya civilization in the southern lowlands collapsed, including overpopulation, environmental degradation, warfare, and prolonged droughts (Nix, 2018). Behind the collapse, archaeologists believed that a combination of factors led to the downfall of this population. In ancient Maya cities, farmers used various techniques to raise enough food to feed the prominent people by raising food in many ways. Together with *Phaseolus vulgaris* (red kidney bean) and *Cucurbita pepo* (true pumpkins), *Zea mays* (corn) was the main staple crop, and each of the three was mutually supportive. Archaeologists discovered that the Mayans produced abundant food to feed their families even though they inhabited land with no metal tools or no draft animals. Due to the diversity of ecosystems, the Maya developed various Mayan farming techniques. Among these techniques are Mayan farming techniques such as shifting agriculture (slash and burn), terrace farming, raised bed farming, and miscellaneous (harvesting wild resources). Today, the Maya reside in their ancestral homelands in Mexico, Guatemala, Belize, Honduras, and El Salvador. These populations also continue to practice their traditional farming methods.

Brief history of Mennonites

The history of Mennonites in Belize can be traced back to 1957. To preserve and search for a life free of religious persecution and the pressures of modern society, the Mennonites relocated to Belize from Germany in the 1950s along the Rio Hondo of Northern Belize (Orange Walk) and the Belize River (Cayo and Belize) (Roessingh and Boersma, 2011). They signed a special agreement with the Belize Government on December 16, 1957; (Saldivar, 2021; Alvarez, 2021), exempting them from military services and certain forms of taxation while guaranteeing them complete freedom to practice their religion and farm within their closed communities. They are expert farmers and agreed to enhance agricultural knowledge in exchange for title to the lands they worked (Awe, 2000), whether that land was suitable or not for farming. Many Mennonite communities in Belize have integrated into modern society, like many other Mennonites. However, the Conservative Mennonite community still exists and assists in the commerce, carpentry, engineering, and agriculture industries. These communities reject the technologies that threaten their established order and the rules that govern their society (Roessingh and Boersma, 2011). This system includes the prohibition of using mobile phones, watching television, and driving cars. However, these individuals can operate heavy machinery that is not of the modern world, such as tractors with rubber tires (Cruz, Michaels, and Lyons, 2018). Typically, they use their heavy machinery to clear forested areas, remove all standing trees, sow, harvest their crops such as corn, wheat, and rice, and make an irrigation system using a nearby water source during the dry seasons. The use of heavy machinery by the conservatives is significant as prime agricultural soil resources, defined as corn, wheat, and soy, are finite, non-renewable, unequally distributed over the geographical regions, and prone to degradation by misuse and mismanagement (Kopitkke et al., 2019).

2. METHODS

Geography, Physiography, and Soils of Belize

Belize is a small Central American nation covering an area of 8867 mi² (22960 km²). The country lies south of the Yucatan Peninsula, sharing a border with the Mexican state of Quintana Roo to the north (Figure 1). Belize shares its western border with the Guatemalan department of Petén and its southern border with the Guatemalan department of Izabal. The Caribbean Sea, with the second-largest barrier reef globally, and various minor islands lie to the east. Due to the abundance of lagoons along the coast and in the northern interior, the actual land area is only 21400 km².



Figure 1. Map of Belize (Young, 2008).

The country's geographical diversity (coastline, mountains, swamps, and tropical jungle) reflects its geological diversity. The most common and prominent geological feature attesting to the patterns of Weaver and Sabido (1997) is the northern plainlands (Figure 2). Located in south-central Belize, the Maya Mountains are the country's oldest geological formation, dating to the Paleozoic (~500 MYBP). Formed from uplifted blocks of intrusive granitic rock and metamorphosed sedimentary rocks, they rise to 1120 meters. The northern half of the country (north of the Maya Mountains) consists of the Yucatan Platform, which contains chalk,

limestone, marl, and other sedimentary layers of approximate mid-Cretaceous age (~90 million years before present [MYBP]) (Weaver and Sabido, 1997). There are other limestone formations and sedimentary rocks south of the mountains. The Coastal Plain, composed of materials from the western highlands, is about 50 km wide in some locations north of the Belize River (Map 5 in Appendix).

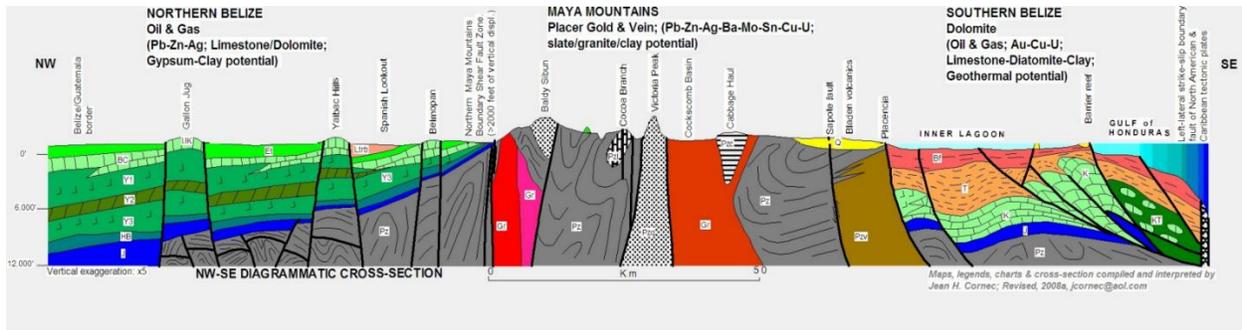


Figure 2: Cross section of the geological features throughout Belize.

The three regions I used for the analyses include different soils (Table 1). There are two significant soils; two major classes: Siliceous and Calcareous in terms of soils. These soils classes generally reflect the principal landforms: calcareous soils of Northern Lowlands (Figure A1), siliceous soils of Mountain Pine Ridge (Figure A2), siliceous soils of Mayan Mountains (Figure A2), and calcareous soils of karst landscapes, tertiary mudstone, shales, and sandstones of Toledo Lowlands (Figure A3), and the littoral complex of organic soils and dunes. Belize has 51% calcareous soils, 37% siliceous soils, and 12% other soil types (Hartshorn, 1984, Wright et al., 1959).

Table 1. Characteristics of each study site.

Features	Study Areas		
	Shipyard	Spanish Lookout	Maya Reserve
Area (hectares)	25900	25900	25900
YEAR 1980 Forest Cover (hectares, %)	3230 (~13%)	7570 (~12%)	52444 (~82%)
Geology	Limestone and Alluvium	Limestone and Alluvium	Granite (acidic), Limestone and Metasediments
Soil Subsuite	Sibal Yalbac Pucte Louisville	Yalbac Pucte	Richardson Suite: Palmasito Xpicilha Hills
Soil (USDA) Type	Sibal = Fluvaquents Yalbac= Vertisols Pucte=Gleysols Louisville=Inceptisols	Yalbac= Vertisols Pucte= Gleysols	Palmasito=Andisols Xpicilha Hills=Vertisol and Inceptisols
Climate (Rainfall)	Max ~500 mm Min ~0	Max ~475 mm Min ~0	Max ~800 mm Min ~0
	<u>Climate</u>		

Belize is a tropical country with a subtropical climate, which indicates that it has two seasons, wet and dry. Most of the year's rainfall occurs from June to November, which is the wet (hurricane) season (National Meteorological Service of Belize [NMSB], 2022). The transition from dry to the wet season can be very sharp (see Appendix Figures A4, A5, and A6). Mean annual rainfall across Belize ranges from 1524 mm (60 inches) in the north to 4064 mm (160 inches) in the south (NMSB 2022). However, the southern region of Belize also shows more significant variability in rainfall from year to year; for example, in 2013, with high mean rainfall of 2249 mm (89 inches). Figure A4 in the Appendix shows the monthly rainfall from the central weather station in the Orange Walk District (Northern region) and encompasses the Shipyard region. The highest monthly recorded rainfall in this region was ~500 mm in November, and the lowest monthly record was 0 mm ranging from January to May of the year (dry season). The Spanish Lookout region experiences a fluctuating rainfall with a monthly maximum record of

~500 mm and a record low of 0 mm between January and early May (Figure A5). Within the southern district, near the Maya Reserve experiences a high record of rainfall in July of ~1500 mm and a low of 0 between February and mid-April (Figure A6).

Background of Communities within the Study Sites

There is an unfortunate error in classifying contemporary images because the satellite images include high cloud cover (Map 1 in Appendix B), which leads to gaps in land cover changes in parts of the country. To overcome this issue, I will compare three parts of the country: Shipyard, Spanish Lookout, and Maya Mountain North Forest Reserve. The comparison will help us identify the trend in forest cover within small-scale farming and large-scale farming. The selection of these study sites relied on the similarity of livelihoods (agriculture), and the distribution represents the country. The primary use of the northern and central districts of Belize is agriculture, whereas the southern district is primarily protected areas, and secondary use is agriculture. Here, I contrast deforestation patterns for three Belizean communities: the Conservative Mennonites of Shipyard, the Progressive Mennonites of Spanish Lookout, and Maya Mountain North Forest Reserve indigenous farmers. Conservative Mennonites resided in rural areas deemed unfit by other nationalities due to the inadequate roads and lack of utilities. Most Belizeans prefer living in areas close to a town, whereas these traditional Mennonites do not rely on modern equipment. In contrast, the progressive Mennonite community in western Belize, Spanish Lookout, relies on modernized equipment, including state-of-the-art machineries such as tractors and soil tillers.

Study Area 1: Shipyard Community (Conservative Mennonite Community)

The Shipyard community was one of the founding societies in 1958 and the greatest Mennonite migrations to Belize, with a population of 3522. Members of the Conservative Mennonite community in Shipyard include some of the oldest and most well-known

establishments in Belize (Humes, 2020). The community owns 6900 hectares, comprising twenty-six local districts called camps (Roessingh and Boersma, 2011). Since Shipyard is an agricultural-based settlement, the land is flat, and cultivated land alternates with land pastures. The primary crops are sorghum, corn, and rice. They also produce tomatoes, melons, cucumbers, sweet peppers, and other vegetables. Livestock is also a prime source of income, and various sawmills provide lumber for houses and furniture.

Study Area 2: Spanish Lookout (Progressive Mennonite Community)

Spanish Lookout was also an essential founding Mennonite community in 1958 as a group of 12 Mennonite settlements known as the Progressive Mennonite community (Roessingh and Boersma, 2011). Its current population is 2500. It lies along the Belize River in the western region of Belize, the Cayo district. This community consists of a modern, adaptive lifestyle distinct from their conservative culture. However, most Mennonite settlements are socially interrelated regardless of contrasting lifestyles and ideological differences. The Progressive Mennonites do not have a ban on technological innovation; they use automobiles and modern machinery in their farm and farm-related businesses (Roessingh and Boersma, 2011). The Spanish Lookout Company plays a significant role in the growth of Belize because it contains Belize's key entrepreneurs in the country. Today, this Mennonite community supplies most of Belize's poultry (Quality Chicken), hardware and building supplies (Farmers Trading Center, Koop Sheet Metal), dairy products (Western Dairies), farming equipment (Gentrac, Caribbean Tires), and animal necessities (Reimers Feed Mill). In addition to these businesses in Spanish Lookout, the community shares its agricultural lands with Belize Natural Energy Limited (BNE, 2019). Shortly after BNE signed its production-sharing agreement with the Government of Belize in 2003, oil exploration began resulting in a discovery in 2005 within various Mennonite-

owned lands (BNE, 2019; Ministry of Economic Development, N.D). Today, oil production is approximately 1030 barrels per day.

Study Area 3: Maya Mountain North Forest Reserve (Maya Farming)

I used this protected area as part of my study area, which exhibits formations by geological uplifting and consists of sedimentary, clastic, volcanic, and alluvial rocks (Wright et al., 1958). My MMNFR site for this research lies northwest of the Cockscomb Basin Wildlife Sanctuary and southwest of Bladen Nature Reserve (Belize Forests Act, CAP.213,2003). The Forest reserve is part of the National Protected Areas System that experiences various threats to the protected area. These threats include wildfires, overhunting, agricultural expansion, and illegal logging. Therefore, as an acting conservation institution, Ya'axche Conservation Trust became the primary manager of this reserve in 2015. As the acting co-manager, Ya'axche Conservation Trust promotes Belize's first concessional agroforestry within a protected area. The aim and purpose of the conservation organization are to provide a livelihood for the inhabitants of the surrounding villages of the indigenous Mayas in Trio village and decrease the need to clear forests for agricultural purposes.

Land Cover Change (Forest Loss)

To conclude land cover change, this study reviews land cover data from existing sources in Belize. Founded on the identification process of land cover types and the definition of specific land cover types. Land cover data were adjusted based on alternative methodologies used in previous studies for comparative purposes. Nevertheless, to highlight the different land types across the country, the data from the project were harmonized by creating three study sites. The study sites included two Mennonite communities, Shipyard and Spanish Lookout, and a conservation area associated with the indigenous Mayan farming population in Belize (Mayan Mountain North Forest Reserve). The two Mennonite farming communities are influential contributors to the increase in deforestation rates throughout Belize.

A substantial part of this study required spatial analysis using a geographic information system (GIS). The software, ArcGIS Pro 2.3, was used for georeferencing the scanned maps of Charles Wright (1958), providing administrative shapefile, mosaicking, and sub-setting of the image based on Area of Interest. The work to quantify provisional soil types and vegetation/land use relied heavily on the wealth of spatial environmental data available in GIS format and from the analysis of geographically referenced maps pioneered by Wright et al.'s group of geologists and surveyors in 1958. The compared maps publicly accessible Landsat time-series dated from 1980 to 2010 from the ArcGIS Hub by Emil Cherrington (2010) and from 2011 to 2020 by Global Forest Watch (2022). The study area's additional datasets include land suitability and ecological features gathered from public resources like USGS Earth Explorer and Google Earth Engine. In addition to the GIS Database, the associated data, such as the tree cover loss and drivers, were incorporated into evaluating the land cover change for the three study sites. Such analysis resulted from post-classified image comparison and pixel trajectory to produce landscape statistics on net land cover change, such as the percentage loss of forest cover between

1980 to 2010 and 2010 to 2020. Using the clip feature in ArcGIS Pro, I created feature classes from the countrywide forest/non-forest polygons to represent each study site and forest fragmentation to determine the deforestation levels between the 40 years, 1980 to 2020. I demarcate the sample area using the fishnet method and calculate the land change per study area per year (Figures 3-6). The cell size used for each study site was a width of 500 m and a height of 500 m. The resulted data provided the number of pixels for each pixel value and further analysed in Excel to categorize the values and calculating the percentage of each study site category. For example, Figure 3 contained a cell covering ~5% of the pixel, ~65% of the cell representing the image, ~25% representing non-forested areas, and ~8% deforested areas (1980-1989). The sum of these areas resulted in a value for the number of hectares of each category (forest, non-forest, deforested). Calculating the land change per study per year, I used the following formula to provide a clear record of the decline and fragmentation of the three study sites of forest stocks:

$$\text{Land Cover Change: } \frac{\text{Sum of deforested areas (ha)}}{\text{Total Study area (ha)}} * 100$$

Where the sum of deforested areas is the total record of deforested areas per study, total record of forested areas, record of non-forested areas and water presence.

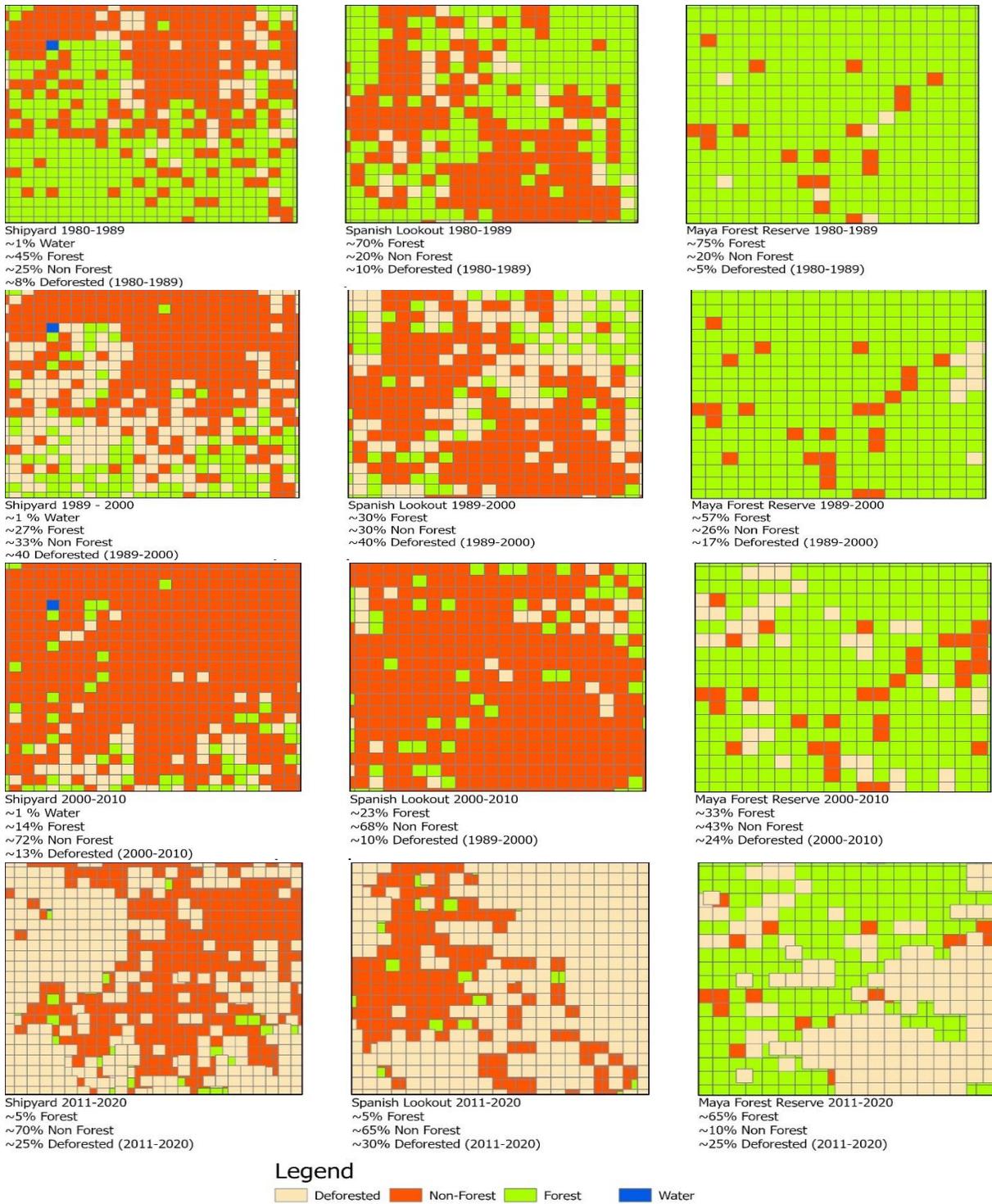


Figure 3. Forest VS Deforested areas within a 10-year period from 1980-2020 per study site

Road Density

Road density is the ratio of the study site's total road network to the site's land area. To investigate the road density of each study site, I used the roads shapefile from Meerman and Clabaugh (2017) (BERDS - Spatial Data Warehouse). Where, I calculated the road density per study site using a simple mathematical formula of dividing the length of road within the polygon by the area resulting in the following equation:

$$\text{RoadDensity (km/km}^2\text{)} = \frac{\text{Road Length (km)}}{\text{Polygon Area (km}^2\text{)}}$$

Drivers to Forest Loss

To determine the dominant drivers of forest loss, I based on numerous sample points and a model using tree-cover information for each cell. The data depicted the dominant driver of tree cover loss in each grid cell and detected four drivers: two major and two minor drivers.

Synthesis

The following synthesis is a compilation of literature from the Montana State University Library systems, primarily the book 'Land of British Honduras' by Wright et al. (1958) and institutional resources. The selection of each article is based on relevance, currency, and accessibility. Each of the examined documents was formally published and subjected to peer review. In addition, I used several federal government publications to evaluate and access current policy and management practices.

3. RESULTS

Land Cover Change 1980-2020

The ArcGIS Pro program enables the calculation of the difference in land cover change using satellite images. Because satellite imagery only extends as far back as 1980, I also scanned historical 1:250000 maps (Wright et al. 1958) for comparisons (Maps 3 and 4 in Appendix B). Over the 30 years between 1980 and 2010, Belize's forest stocks declined from 75.9% to 62.7% (324,000 hectares) for an approximate annual deforestation rate of ~10000 hectares per year from late 1980 to early 2010 (Cherrington et al., 2010). During the decade of the 1990s (1989 and 2000; Map 2; Cherrington et al., 2010), deforestation was at its greatest. As a result of these two study sites, Shipyard and Spanish Lookout contributed the most to the loss of forest cover between 1990 and 2000, with ~ 38% (Table 4). Over the past 40 years, the Shipyard community has lost over 3000 hectares of forest to deforestation. In contrast to the Mennonite Communities, the Maya Reserve had the lowest forest loss of ~770 hectares (1%) over the ten years (2000 to 2010; Map 2; Cherrington et al., 2010). However, between the 2010 and 2020 periods, there was a spike in forest loss (~1000 hectares). Cumulatively, Shipyard contributed the highest rate of deforestation at 51%, followed by Spanish lookout at 40%. In contrast to the Mennonite communities, the protected area Maya Reserve has a 19% change. Figure 4 portrayed Spanish Lookout as the primary contributor to forest cover loss in 1980, followed by Shipyard at a lower percentage but the highest in the 2000s. After early 2000, Shipyard remained the highest contributor to forest loss between 2000 and 2020.

Table 2. Estimated decadal deforestation areas (ha) by site, 1980 to 2020.

Study Sites

Description	Shipyard	Spanish Lookout	Maya Mountain Forest Reserve
Deforested (1980-1989) (Cherrington et al, 2010)	681	1745	148
Deforested (1989-2000) (Cherrington et al, 2010)	5357	4446	622
Deforested (2000-2010) (Cherrington et al, 2010)	3579	1917	1323
Deforested (2010-2020) (Global Forest Watch, 2020)	3309	2414	2314

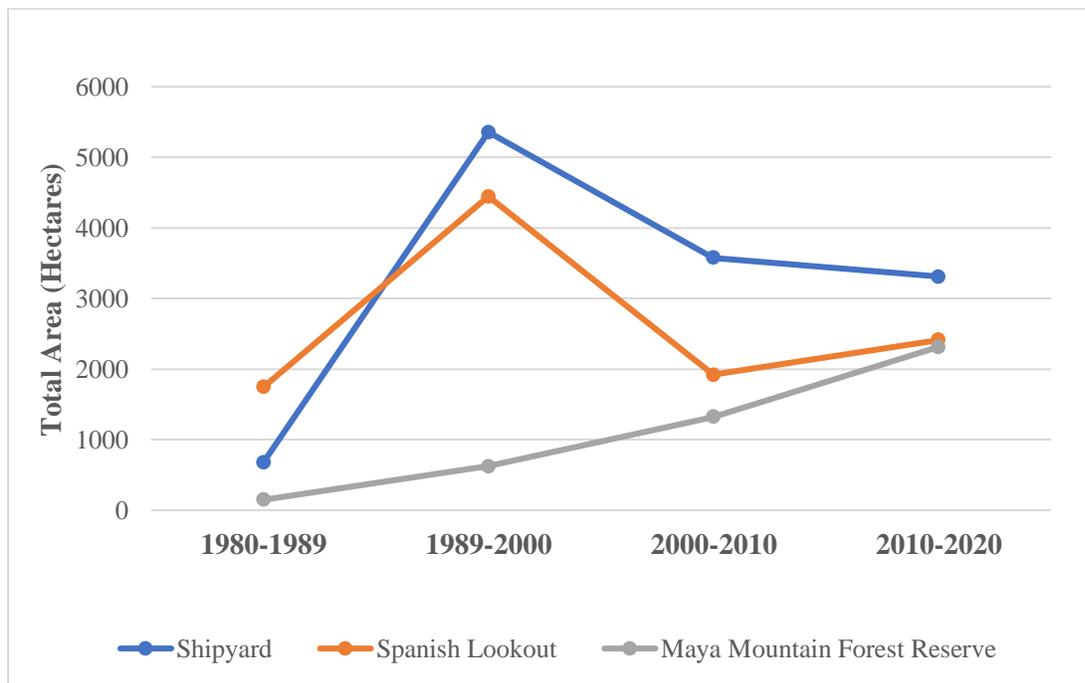


Figure 4. Graph showing the deforestation rate from 1980-2020 within the study sites.

Table 3. Total area and percentage of forested areas per study site from 1980-2020

Category	Shipyard	Spanish Lookout	Maya Mountain Forest Reserve	Total
All land cover (hectares)	25900	25900	25900	77700
1980-2010 imagery source	Cherrington et al (2010)	Cherrington et al (2010)	Cherrington et al (2010)	Cherrington et al (2010)
2010-2020 imagery source	Global Forest Watch (2022)	Global Forest Watch (2022)	Global Forest Watch (2022)	Global Forest Watch (2022)
% Deforest -1990	3	7	1	3
% Deforest -2000	21	17	2	13
% Deforest -2010	14	7	5	9
% Deforest -2020	13	9	9	6
Cumulative % deforestation 1980-2020	51	40	17	31

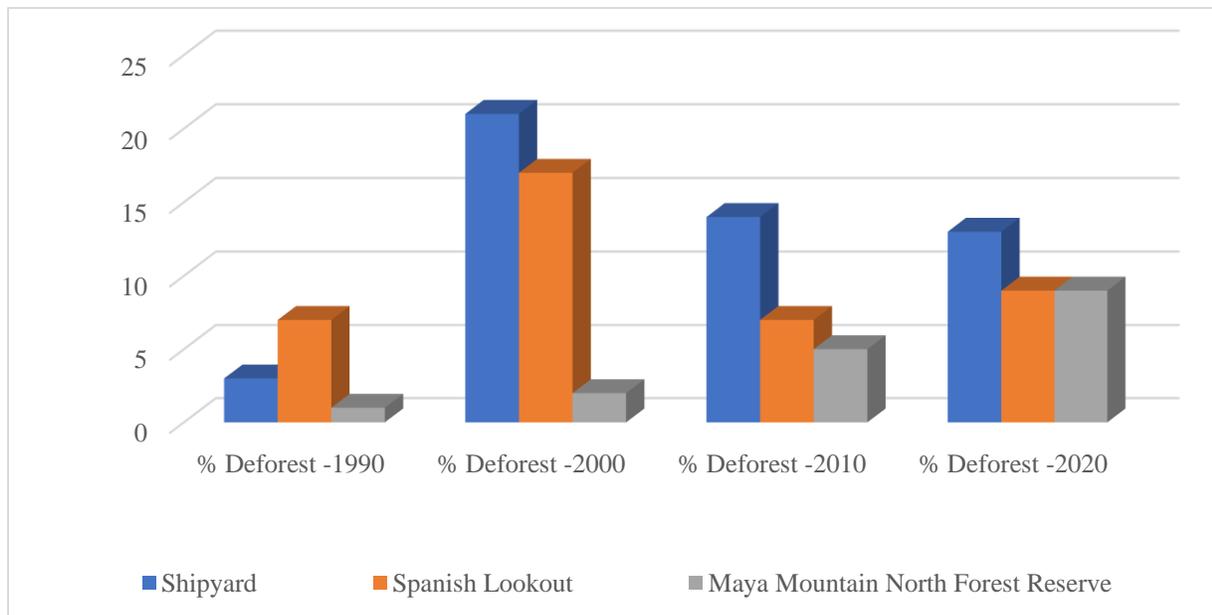


Figure 5. Percentage of deforestation from 1980-2020.

Drivers to Forest Loss

As noted in the previous section, forest cover loss is steadily increasing. Every ten years, there is approximately a 10% loss. With the continuous forest loss, four main drivers were

identified (Global Forest Watch, 2022): Commodity driven, Forestry, Shifting agriculture, and Unknown. Deforestation has occurred predominantly near areas with existing traffic infrastructures within the last 20 years (Map 2). Commodity driven and Shifting agriculture are the dominant drivers of tree cover loss (Figure 6). Commodity-driven deforestation includes large-scale deforestation linked primarily to commercial agricultural expansion. Followed by the second prevalent driver, Shifting Agriculture, is the temporary loss or permanent deforestation due to small- and medium-scale agriculture. As depicted on Map 2, large-scale agriculture existed on large parcels of cleared cut lands within the Shipyard and Spanish Lookout communities. These expansions also relate to the existing road infrastructures.

In contrast to the large-scale farming communities, the small and medium-scale farming within the Maya Mountain North Forest Reserve occurs in small portions and a scattered pattern along the borders of the protected area. Minor forest loss drivers consist of forestry and an unknown category. Tree loss due to forestry includes the temporary loss from the plantation and natural forest harvesting, with some deforestation of primary forests. The 'unknown' driver category consists of several factors such as wildfires and urbanization. However, the data set does not indicate whether wildfires occurred due to natural causes or anthropogenically, categorized as unknown.

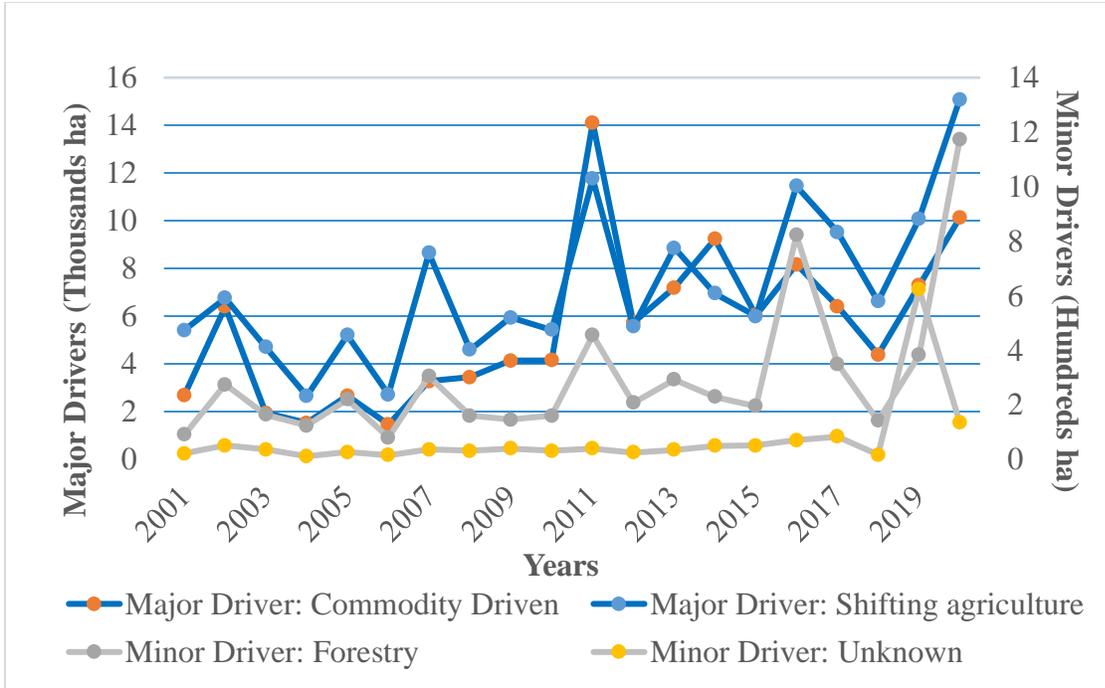


Figure 6 Tree cover loss drivers, 2000 to 2020 (Global Forest Watch, 2022).

In 2020, Belize experienced the highest forestry-related activities, such as logging.

Deforestation and sustainable logging concession contribute to the spiked activity (Figure 6).

Upon clearing the land for agricultural purposes, individuals use the fallen trees as timber for personal construction, furniture making, or other materials. Sustainable logging concession consists of either secondary forests or plantations of a specific species. These species include the mahogany (*Swietenia*) species, pine (*Pinus caribbea*) trees, and teak (*Tectona grandis*).

Road Density

The roads in the area studied are described as a secondary network that thrives within villages. In Shipyard, Spanish Lookout, and Maya Forest, roads built are for agricultural needs: forestry and general farming. In a recent article about the Amazon Forest in Brazil, Vilela, 2020 state that the increase in road networks is permanently altering the world's largest tropical forest. However, in comparison to the Amazon Forest in Brazil, Belize experienced a decrease over the years and did not promote deforestation. As calculated in Table 4, Shipyard and Spanish Lookout experienced a decrease in road density, especially the Spanish Lookout community. This community lost ~100 km of roads from 2008 to 2020, and one assumption deduced from this analysis indicated that the primary contributing factor to the road deterioration was soil loss due to erosion caused by heavy rainfall during the wet season. Another assumption for the disappearance of these roads is the conversion of roads to croplands. Hence, the decrease in the road densities overtime per study site, except for the Maya Mountain North Forest Reserve. The Maya Mountain North Forest Reserve experienced no changes as the Mayans primary mode of transportations are bicycles and walking. The overall quality of these road networks varies from poor to fair, indicating a rapid deterioration. From 2007 to 2008, 5 to 12% of the road system was considered fair to poor condition; between 2012 to 2013, it was nearly 60% (Inter-American Development Bank, 2013).

Table 4. Road density per study site

	Shipyard	Spanish Lookout	Maya Mountain North Forest Reserve
Road Density 2008	193 km/km ²	264 km/km ²	8 km/km ²
Road Density 2020	160 km/km ²	165 km/km ²	8 km/km ²

4. DISCUSSION

Land cover and use are inherently coupled: land-use practices can change the land cover, and land cover enables specific land uses. The resulting changes in land cover are the response to both human and climate drivers. For example, the demand for agricultural expansions often results in the permanent loss of natural and working lands, resulting in localized weather patterns and precipitation (Loveland et al., 2018). In Belize, the vegetated land cover, including lowland forests, broadleaf forests, and wetlands, accounted for approximately ~55% in 2020 (Global Forest Watch, 2022). The loss of forest cover from 1980 to 2020 represents a decline of 0.5% annually. This decline falls slightly below the Cherrington et al. (2010) calculations of 0.6% annual rate of forest loss between 1980 and 2010 and below the Folklard-Tapp (2018) calculation of 0.89% yearly forest loss. Percentage loss was considered the most appropriate measure for comparing land cover loss and real-world effects (soil erosion) to the loss of land cover changes. Due to its real-world management implications, inevitable forest loss remains a relevant consideration when investigating reasons for the deterioration of land cover and its effects on soil fertility. Therefore, limiting the influence of the cause of land cover change in Belize allows for other factors such as considering the existence of protected areas.

In Belize, only 13% of the land falls under the category of biodiversity reserve, the rest being extractive reserves that allow timber, flora, and fauna to be cut and removed (Folklard-Tapp, 2018). Adding to extractive reserves, privately-owned territories in northern Belize, most of Belize's protected areas lie towards the south when the Forestry Trust and Forest Department first established protected areas in 1923 and 1939, respectively (King et al., 1992). The study sites Shipyard, Spanish Lookout, and Maya Mountain North Forest Reserve are current spots of interest. As a result, the detected forest loss occurred predominantly within the Shipyard and Mennonite communities. Here were the highest levels of deforestation in the 1990s (1990 to 2000) in the northern district of Orange Walk, characterized by extensive agriculture

(Cherrington et al., 2010). Over the past 40 years, the decadal 1990-2000 portrayed the highest record of deforestation activities between the Shipyard community losing ~20% of forest for agriculture expansion, followed by the Spanish Lookout community, which lost 17% of their forest cover. In contrast to the Mennonite Communities, the Maya Reserve had its highest forest loss of 9% from 2010 to 2020; (Map 2; Cherrington et al., 2010). Cumulatively, Shipyard contributed the highest rate of deforestation at 51%, followed by Spanish Lookout at 40%. In contrast to the Mennonite communities, the protected area Maya Reserve has a 19% change.

Interestingly, the Mayans' beliefs rely heavily on sustainability, regardless of the Mayan history of extensive farming and various farming techniques, unlike the Mennonite communities, which practice large-scale farming as a commodity. As a result, agricultural expansion correlates with the complex roadway networks within the Shipyard and Spanish Lookout communities (Map 2). Although they are secondary road networks, most of these roads are of low quality and prone to degradation, primarily soil erosion due to heavy machinery traffic and flooding from heavy rainfall. Due to the diverse vegetation across the country and weather patterns, it is questionable that all adjacent areas are suitable (fertile, sufficient moisture, drainage) for agricultural activities. The assessment of the northern region of Belize resulted as a nutrient-poor with *good chances of agricultural capacity* (King et al., 1992; Wells et al., 2018). Charles Wright et al. (1959) proposed potential land uses, as shown in Map 4, according to the provisional soil types of Belize. For the Northern Region of Belize, Wright proposed that the land use was primarily for orchard crops, short rotational pasture, and some sugarcane farming. Therefore, the Shipyard community consisted primarily of short rotational pasture, orchard crops, Mahogany forests, and sugar cane farming. Spanish Lookout community area consists of Long Rotation Pasture, with portions of its areas designated for mahogany (*Swietenia macrophylla*) Forests, sugar cane farming, and sustainable pine (*Pinus caribaea*) forest logging.

Maya Mountain North Forest Reserve consists of Protection forests, orchard crops, and sustainable pine forests.

Belize exhibits a spatial, graphic representation of soil productivity and infertility associated with agricultural capacity according to its location within the subtropical climate, lithology, and terrain (Map 6 in Appendix) (King et al. 1992). Despite the 2–the 5-month dry season when hardly any or no rain falls, the soils are moist for most of the year, which makes a large amount of weathering and biological activity occur. Therefore, the soils are subject to leaching, either moderate or intense (King et al. 1992). Northern Belize consists of various main soil suites under the Spanish Lookout and Shipyard communities, such as the Yalbac and Pucte. The first significant soil suite is the Yaxa Suites containing the Yalbac subsuite and all clays overlying the Late Cretaceous (~60 million years ago) to Early Tertiary (~36 million years ago) limestones. These soils exhibit fine textures, neutral or alkaline pH values, and exceedingly high base cation saturation due to elevated calcium levels. An extensive network of soils throughout the country sustains clear-cut lowland forests and intensive agricultural production. The Yalbac soils exhibit characteristics of black, dark grey, or greyish brown clays at varying depths and with decent drainage. The NCRS (soil taxonomy) consists of soil type, vertisol, fluvisols, gleysols, and inceptisols. Its landform entails the upper part of the low flat rise in a gently undulating plain in the Shipyard Plainland system that derives from the limestone parent material. Most well-drained sites support semi-deciduous broadleaf forests, while it sustains the lowland broadleaf forests in low-lying areas. However, limitations of these soils exist considerably according to the morphological range. The shallower soils tend to be droughty in dry weather, whereas imperfect drainage and poor subsoil aeration in wet weather will affect the deep-blotched profiles. An additional limitation that arises with farmlands on these types of soils is the apparent threat of gully erosion, dry season moisture deficiency in shallow soils, and an

excess of wet season moisture. These soils tend to be less well-endowed with phosphate and potassium, indicating a nutrient imbalance.

Nonetheless, the soil is fertile, whereby extensive agriculture will not require heavy inputs of fertilization. Therefore, the suggested land use for these soils is cereals and pasture (King et al., 1992; Wright et al., 1958), of which is the primary land use by both Mennonite communities. Secondly, the Maya Mountain North Forest Reserve sits on the Richardson Suite, which includes all soils developed on the rocks of the Bladen volcanic member of the Santa Rosa Group (King et al., 1992, Baetson and Hall, 1977). Due to its characteristics, the appropriate and well-defined soil group for the MMNFR was the Palmasito soil. The soils appear to be young soils on volcanic parent materials, Andisols, in the current version of the NRCS Soil Taxonomy. Its characteristics entail red and yellow, very acidic, and leached soils. These soils are of medium and refined textures over deeply weathered metandesite or metayhyolite and have high moisture capacity. They sustain tall forest with abundant palms-on crests and numerous large Santa Maria on slopes. Undistributed yet, geographically and topographically unsuited to agricultural development, highly erodible when natural forest cleared. Other parts of the area consist of the Xpicilha Hill, vertisols, and inceptisols soils.

With the soil classifications of the Northern region and agricultural capacity, the Shipyard community has *a good chance of success* within the limestone and alluvial region that consists mainly of vertisol, gleysols, and cambisols (Map 5, Map 6). A *good chance of success* implies a relatively low chance of soil erosion, unbalanced pH, and fluctuating weather of precipitation and evapotranspiration. This region encompasses primarily flat terrain with diverse flora and fauna, including broadleaf forests, marsh forests, and wetlands. There are also pine forests as well as low broadleaf forests (Map 3). As part of its topographical feature, this region supports a mixture of two dominant vegetation types: marsh forests/wetlands and lowland

broadleaf forests (Map 3). According to the NRCS, vertisol is fertile clay-rich soil that contains an expansive type of clay, allowing it to shrink when dry and swell when wet. Therefore, it is also evident that agricultural activities have a good chance of success in the central region, as exhibited in Map 6 for the Spanish Lookout community. However, this region also exhibits both moderate and marginal chances for success. The reason is that the Spanish Lookout experiences a longer rainfall record during the wet season.

In contrast to the north, the southern study area has a moderate and low potential for agricultural capacity (Map 6) due to the high amount of highly weathered andisols, vertic, and rendollic eutrochrepts. According to NRCS, they are prone to degradation due to the highest rainfall record and extended periods of rainfall than the rest of the country. Therefore, the agricultural capacity ranges from high to low chances of success (Map 6). These features support Broadleaf Forest with Karst and Submontane Broadleaf Forest (Map 3), which covers a large area of metasediments (limestone, shale, slates, and marble) and granitic geological platforms (Map 5). However, most of the trending land conversions occur within the areas of moderate and marginal chances of success. According to King et al. (1992), the reason relies primarily on the soil type, geological features, and climate. King (1992) suggested that these areas remain forested and protected to prevent erosion and landslides.

With the increase in global food security demands, the communities within the study sites rely on agriculture for their livelihood. As a result, these farmers depend on road infrastructures to labor their lands. Due to the specific purpose of roads being for agriculture, the networks are not of an adequate standard, meaning low quality unpaved (feeder) roads and lack drainage. Such road qualities are prone to degradation during the wet season as heavy rainfall floods the road causing the roads to deteriorate. This circumstance provides sight that roads generate erosions

and increase during heavy rainfalls. Such occurrence results from land degradation, soil erosion, and poor planning. As identified in this study, the road density decreased within ~12 years. The land cover change with other factors such as rainfall patterns, resulting in soil deterioration such as soil erosion and soil structure, and indicate differences in agricultural status. These differences and distances to forests are reflected in commodities, shifting agriculture, and beliefs. The dominant driver for the last 20 years, as noted earlier, are both commodity-driven deforestation and shifting agriculture. Commodity-driven deforestation consists of large-scale deforestation linked primarily to commercial (large-scale) agriculture expansion, representing permanent deforestation, mainly practiced by the Mennonite communities of Shipyard and Spanish Lookout. Whereas shifting agricultural deforestation is temporary loss or permanent deforestation due to small and medium scale agriculture. This agricultural practice occurs within the indigenous Mayan communities in southern Belize and among local farmers in smaller villages throughout the country. In contrast to commodity-driven deforestation, shifting agriculture does not represent permanent deforestation; instead, the affected tree cover often regrows. Therefore, cumulatively the three study sites encompassed 22% of the total agricultural land within the country, that is ~38800 hectares (The World Bank, 2022). Compared to the global rankings, the average agricultural land in 193 countries was ~253,000 square miles (~65 million hectares) (The World Bank, 2022). By this ranking, it is evident that Mennonite communities form a significant aspect of the agricultural sector.

5. RECOMMENDATIONS FOR FUTURE WORK

Compared to other countries, the deforestation rates of Belize are relatively low. Belize is a small country of 8867 mi², and the deforestation rate is alarming, especially within the Mennonite communities. With the fluctuating weather patterns (lower rainfall and extended droughts), concerns associated with land degradation rise. The northern (Orange Walk) and central (Cayo) districts are areas of interest due to their vital part of the Mesoamerican Biological Corridor and the Selva Maya Region. The Selva Maya lies at the intersection of Belize, Guatemala, and Mexico. More importantly, within the Cayo district, because of the expansion of Spanish Lookout, farming communities occur along the borders of the Rio Bravo Reserve. In 2021, more than a dozen conservation organizations purchased a critical piece of land, Belize Maya Forest, a former forestry concession, from being cleared for industrial-scale agriculture. Within the Shipyard community, there is no existing conservation organization as there is no stakeholder engagement with the conservative Mennonites (Brock et al., 2018). The Mennonites found in Shipyard were not the only conservative ethnic group, but so were the Mayas in southern Belize. These individuals follow their tradition and culture as it continues from generation to generation. In 2015, the Ya'axche Conservation Trust became the co-manager of the Maya Mountain North Forest Reserve. This organization prioritized the necessity of stakeholder engagement and achieved remarkable success in implementing sustainable farming within the Maya culture. Stakeholder engagement is the primary principle of expecting positive results (Zabinski, C, 2021, personal communication). Therefore, I recommend a similar procedure within the conservative Mennonite communities, both in Shipyard and throughout Belize. Another recommendation for future projects would be ground-truthing to update the datasets for road networks and identify road networks' maintenance (conversion or disappearance).

6. CONCLUSIONS

Deforestation rates in 2020 and earlier are different for distinct parts of Belize, especially within the study areas of Shipyard (north), Spanish Lookout (central), and Maya Forest Reserve (south). There are diverse cultures in each study area regarding inhabitants, Mennonites in both Shipyard and Spanish Lookout, and the Mayas in Maya Forest Reserve. The Mennonites are recent inhabitants dating to the late 1950s. In contrast to this ethnicity, the Mayas lived in Belize for more than 1,000 years, where the Mayan population flourished before the conquistadors travelled the western hemisphere. Evidence of their existence is present as ceremonial sites and temples that dot landscapes throughout Central America, such as Belize, Guatemala, and Mexico. Currently, archaeologists carry out assorted studies to understand their downfall, livelihood, and linkages with surrounding areas. Archaeologists deduced that only 40% of Belize might have been forested because of 11 partly or wholly excavated Mayan archaeological sites. These sites were home to at least one million Mayas. By 1960, Charles Wright estimated 88% of Belize was forested and estimated forest cover for each study area as ~13 % in Shipyard, ~20% in Spanish Lookout, and ~40% in the Maya Reserve. With the soil classifications of the Northern region, there is high potential for agricultural activities as most of the study areas consisted of vertisols, which are fertile and recommended for agriculture. In contrast to the northern study sites, deforestation occurs on relatively less fertile soils which leads to higher rates of persistent land degradation such as soil erosion, mudslides, and flooding in the southern study site (MMNFR).

Based on the multi-temporal automated classification of satellite imagery of Belize by secondary sources, it was evident that Belize's forest cover has declined over the last 40 years, as indicated by previous studies done by Cherrington et al. (2010) and by Global Forest Watch (2022). Compared to other countries, the deforestation rates of Belize are relatively low. However, the deforestation rate is alarming for a small country of 8867 mi², especially within the

Mennonite communities. The Mennonite communities are great entrepreneurs and farmers; therefore, I agree with the Global Forest Watch (2022) that the main driver of forest cover loss is commodity-driven (large-scale agriculture). The forest cover lost within the Maya Mountain North Forest Reserve was too small-scale and temporary agriculture due to the community focusing on their personal needs rather than partaking in the economic sector. This agricultural practice occurs within the indigenous Mayan communities in southern Belize and among local farmers in smaller villages throughout the country. Lastly, the three study sites consisted of an extensive road network consists of two main categories: paved and unpaved roads. Most agricultural-related road networks are unpaved (feeder) roads that are poorly maintained and prone to degradation. Evidence of degradation was seen through the decrease of road density within the Shipyard and Spanish Lookout communities. Therefore, the analysis suggested that road networks were not the primary reason for deforestation.

REFERENCES CITED:

- Alvarez, V. and Saldivar, A. (2021). Arthur Saldivar Says an Initial Agreement between British Honduras and the Mennonite Community Still Stand. *Love FM News*: Website: <https://lovefm.com/arthur-saldivar-says-an-initial-agreement-between-british-honduras-and-the-mennonite-community-still-stand/>
- Beach, T., Dunning, N., Luzzadder-Beach, S., & Scarborough, V. (2003). Depression Soils in the Lowland Tropics of North-western Belize: Anthropogenic and Natural Origins. *Geoscience*. Chapter 8.
- Beach, T., and N. P. Dunning. 1995. Ancient Maya terracing and modern conservation in the Petén Rain Forest of Guatemala. *Journal of Soil and Water Conservation* 50:138–145.
- Beaton, M. (2019). Belize’s First Agroforestry Concession for Conservation & Livelihoods: A Case Study Report 2019. *Ya’axche Conservation Trust*. Retrieved from <https://yaaxche.org/wp-content/uploads/2019>
- Belize Forest Act. Chapter 213. Revised Edition (2003). Retrieved from: <http://www.belize.gov.bz/web/lawadmin/PDF%20files/cap213s.pdf>
- Belize Natural Energy Limited (2019). About BNE and its Milestone. Retrieved from <https://www.bne.bz/message-from-the-ceo-2018/milestones/>
- Berry et al. (2020). Evaluating ecosystem services trade-offs along a land-use intensification gradient in central Veracruz, Mexico. *Ecosystem Services*. 45. (101181). <https://doi.org/10.1016/j.ecoser.2020.101181>
- Bridgewater, S. 2012. *A Natural History of Belize: inside the Maya Forest*, University of Texas Press, Austin.
- Briggs, V.S., R.G. Harvey, F.J. Mazzotti, T.K. Barnes, R. Manzanero, J.C. Meerman, P. Walker, and Z. Walker. 2013. A conceptual ecological model of the Chiquibul/Maya Mountain Massif, Belize. *Human and Ecological Risk Assessment* 19:317-340.
- Brock, C., Ulrich-Schad, J., & Prokopy, L. (2018). Briding the Divide: Challenges and Opportunities for Public Sector Agricultural Professionals Working with Amish and Mennonite Producers on Conservation. *Environmental Management* 62, 756-771. <https://doi.org/10.1007/s00267-018-0998-5>
- Bushong, A. (1961). *Agricultural Settlement in British Honduras: A Geographic Interpretation of its Development*. Dissertation presented to the Graduate Council of the University of Florida.
- Carrie, R. and Kay, E. (2014). Belize. In: Alonso Egui-Lis, P, Mora Tavarez, M., Campbell, B and Springer, M, (eds.) *Diversidad, conservacion y uso de los macroinvertebrados dulceacuicolas de Mexico, Centroamerica, Colombia, Cuba y Puerto Rico*. Instituto Mexicano de Tecnologia del Agua, Mexico. Pp. 33-61. ISBN 978-607-9368-21-0

- Cherrington, E.A., Ek, E., Cho, P., Howell, B.F., Hernandez, B.E., Anderson, E.R., Flores, A.I., Garcia, B. C., Sempris, A. & Irwin, D.E. 2010. Forest Cover and Deforestation in Belize: 1980-2010. Panama, Panama City: Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC).
- Cherrington, E.A., Cho, P.P., Waight, I., Santos, T.Y., Escalante, A.E., Nabet, J. & Usher, L. 2012. Executive Summary: Forest Cover and Deforestation in Belize, 2010-2012, CATHALAC, Panama City, Panama.
- Cruz, D., Michaels, J., & Lyons, E. (2018). A Simple Life: Mennonites living in Belize exist apart from the government, with limited technology and surrounded by farmable land. *The New York Times: The Look*. Retrieved from online website: <https://www.nytimes.com/2018/09/15/style/mennonites-belize.html>
- Doyle, C., Beach, T., & Luzzadder- Beach, S. (2021). Tropical Forest and Wetland Losses and the Role of Protected Areas in North-western Belize, Revealed from Landsat, and Machine Learning. *Remote Sensing*. 13, (379). <https://doi.org/10.3390/rs13030379>
- Global Forest Watch. (2022). Forest Monitoring Designed for Action: Belize Map. Retrieved from website: <https://www.globalforestwatch.org/>
- Guerrero-Garcia, J., and Herrero-Bervera, E. (2012). On the Reliability (Remagnetization?) of Paleomagnetic Poles Obtained from Permo-Silurian Rocks from Oaxaca Mexico, Belize, and Guatemala: Insights from Rock Magnetic Studies. *Open Journal of Geology*, 2. 48-56 <http://dx.doi.org/10.4236/ojg.2012.22005>
- Hannah Ritchie and Max Roser (2021). “Forests and Deforestation”. *Published online at OurWorldInData.org*. Retrieved from: [Deforestation and Forest Loss - Our World in Data](https://ourworldindata.org/deforestation-and-forest-loss)
- Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. (2022). “High-Resolution Global Maps of 21st-Century Forest Cover Change.” *Science* 342 (15 November): 850–53. Data available on-line from: <http://earthenginepartners.appspot.com/science-2013-global-forest>.
- Hayes, Daniel J., Steven A. Sader, and Norman B. Schwartz. 2002. Analyzing a Forest Conversion History Database to Explore the Spatial and Temporal Characteristics of Land Cover Change in Guatemala’s Maya Biosphere Reserve. *Landscape Ecology*. 17: 299:314.
- Hightower, Jessica N., "Relating Ancient Maya Land Use Legacies to The Contemporary Forest of Caracol, Belize" (2012). Electronic Theses and Dissertations, 2004-2019. 2455. <https://stars.library.ucf.edu/etd/2455>
- Hoggarth, J., Restall, M., Wood, J., & Kennett, D. (2017). Drought and its Demographic Effects in the Maya Lowlands. *Current Anthropology*, Vol. 58, No. 1 Retrieved from: <https://www.journals.uchicago.edu/doi/epdf/10.1086/690046>

- International Trade Administration. (2021). Belize- Country Commercial Guide. Retrieved from: <https://www.trade.gov/country-commercial-guides/belize-agriculture-and-agro-processing>
- King, R. B., I. Baillie, T. Abell, J. Dunsmore, D. Gray, J. Pratt, H. Versy, A. Wright, and S. Zisman. 1992. Land resource assessment of Northern Belize. Bulletin 43, Natural Resources Institute, Overseas Development Administration. Hobbs the Printers of Southhampton, U.K.
- Kopittke, P., Menzies, N., Wang, P., McKenna, M. & Lombi, E. (2019). Soil and the intensification of agriculture for global security. *Environmental International*. Vol. 132, <https://doi.org/10.1016/j.envint.2019.105078>
- Mann, C. (2011). 1491: New Revelation of the Americas before Columbus. *Vintage Books: A Division of Random House, Inc. New York*. Second Edition. Ebook ISBN: 9780307278180
- McNish, B., & Granada, I. (2013). Transport Sector in Belize. *Inter-American Development Bank*. Retrieved from: <https://publications.iadb.org/publications/english/document/Transport-Sector-in-Belize.pdf>
- Meerman, J.C. & W. Sabido. 2001. “Central American Ecosystems Map: Belize.” Volumes I. Programme for Belize. Belize City, Belize. 28 pp. Available online: http://biologicaldiversity.info/Downloads/Volume_Iweb_s.pdf
- Meerman, J.C. & Cherrington, E. (2005). Preliminary Survey of Land Degradation in Belize. *United Nations Convention to Combat Desertification*. [\(PDF\) Preliminary Survey of Land Degradation in Belize \(researchgate.net\)](#)
- Meerman, J. and Clabaugh, J. (2017). Biodiversity and Environmental Resource Data System of Belize. Online. [BERDS - Spatial Data Warehouse \(biodiversity.bz\)](#)
- Miller, T. (1996). Geologic and Hydrologic Controls on Karst and Cave Development in Belize. *Journal of Cave and Karst Studies*. 58(2): 100-120. [\(PDF\) Geologic and hydrologic controls on karst and cave development in Belize \(researchgate.net\)](#)
- Ministry of Economic Development. (N.D). Belize Petroleum Industry. Retrieved from website: <https://med.gov.bz/belize-petroleum-industry/>
- Moore, M. (2007). An examination of contributing factors to land use/land cover change in southern Belize and the use of satellite mage analysis to track changes. Iowa State University. *Retrospective Theses and Dissertations*. <https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=16083&context=rttd>
- Morris, R. (2010). Anthropogenic impacts on tropical forest biodiversity: a network structure and ecosystem functioning perspective. *The Royal Society Publishing: Philos Trans R Soc. Land B. Bio. Sci.* 365(1558). doi: [10.1098/rstb.2010.0273](https://doi.org/10.1098/rstb.2010.0273)

- National Meteorological Service of Belize. (2022). Climate Summary: The Climate of Belize. Retrieved from: <http://nms.gov.bz/climate-services/climate-summary/>
- O'Neill, A. (2022). Share of Economic Sectors in GDP in Belize 2020. *Statista: Economy & Politics*. <https://www.statista.com/statistics/727205/share-of-economic-sectors-in-the-gdp-in-belize>.
- Penner, D. (2012). A Video Documentary of Life in Spanish Lookout, Belize from 1958 to 2008. *Shamax Productions*: Retrieved from <https://www.youtube.com/watch?v=cqQLhLfdgu0>
- Patterson, C. (2014). Deforestation, agricultural intensification, and farm resilience in Northern Belize: 1980-2010. Thesis for the degree of Doctor of Philosophy at the University of Otago, New Zealand.
- Polanco, A. (2020). Belize Leads in Protection of Land and Sea- But We're Not Stopping There! *Oceana: Protecting the World's Ocean*. Retrieved from: [OceanaBelize](https://oceana.org/belize)
- Porter, S. & Rice, K. (2012). Trade-offs, spatial heterogeneity, and the maintenance of microbial diversity. *Evolution*. 67(2): 599-608. DOI: [10.1111/j.1558-5646.2012.01788.x](https://doi.org/10.1111/j.1558-5646.2012.01788.x)
- Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+). 2021. Website <https://www.redd.plus/countries/belize>
- Roessingh C., and Boersma, K. (2011). 'We are growing Belize': Modernisation and organisational change in the Mennonite settlement of Spanish Lookout, Belize. *Int/ J. Entrepreneurship and Small Business, Vol. 14, No.2, 2011* \. Retrieved from: <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.952.1543&rep=rep1&type=pdf>
- Sleeter, B., Loveland, T., Domke, G., Herold, N., Wickham, J., & Wood., N. (2018). Land Cover and Land-Use Change. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume 2* U.S. Global Change Research Program, Washington, DC, USA, pp 202-231 doi: 10.7930/NCA4.2018.CH5
- Soil Survey Staff. 1998. Keys to soil taxonomy. 8th ed. U.S. Department of Agriculture, Natural Resources Conservation Service. U.S. Government Printing Office, Washington, D.C.
- Trenda, E. (2022). Latin America: agricultural sector's share of GDP 2019, by country. *Statista*: Retrieved from: <https://www.statista.com/statistics/1079120/latin-america-caribbean-agriculture-share-gdp/>
- United Nations Convention to Combat Desertification. (2017). Global Land Outlook: Chapter 7 Biodiversity and Soil. Pdf. [Chapter 9: Biodiversity and Soil | Knowledge Hub \(unccd.int\)](https://www.unccd.int/knowledge-hub/biodiversity-and-soil)
- United States Energy Information Administration. (2022). Drilling Productivity Report. Retrieved from website: <https://www.eia.gov/petroleum/drilling/pdf/dpr-full.pdf>

- Vilela, T., Harb, A., Bruner, A., & Botero, R. (2020). A better Amazon road network for people and the environment. *PNAS: Research Article*. <https://doi.org/10.1073/pnas.1910853117>
- Wells, G., Stuart, N., Furley, P., & Ryan, C. (2018). Ecosystem service analysis in marginal agricultural lands: A case study in Belize. *Ecosystem Services*. 32 (70-77). <https://doi.org/10.1016/j.ecoser.2018.06.002>
- World Wildlife Fund (2020). Tropical Rainforest. Retrieved from Online Website: https://wwf.panda.org/discover/our_focus/forests_practice/importance_forests/tropical_rain_forest/
- Wyman, M. & Stein, T. (2010). Modelling social and land-use/land-cover change data to assess drivers of smallholder deforestation in Belize. *Applied Geography*. 30 (329-342). . doi:10.1016/j.apgeog.2009.10.001
- Wright, J. (2010). The future of tropical forests. *Annals of the New York Academy of Science*. 1195. 1-27 doi: 10.1111/j.1749-6632.2010.05455.x
- Wright, A.C.S., Romney, D.H., Arbuckle, R.H., and V.E. Vial. 1959. "Land in British Honduras." Colonial Research Publication No. 24. Her Majesty's Stationary Office. London, England. 325 pp.
- Young, C. 2008. Belize's Ecosystems: Threats and Challenges to Conservation in Belize. *Tropical Conservation Science* 1(1):18-33. Available online: tropicalconservationscience.org
- Zabinski, C. (2021, November) *Personal Communication*. [Class Presentation].

APPENDIX A: FIGURES

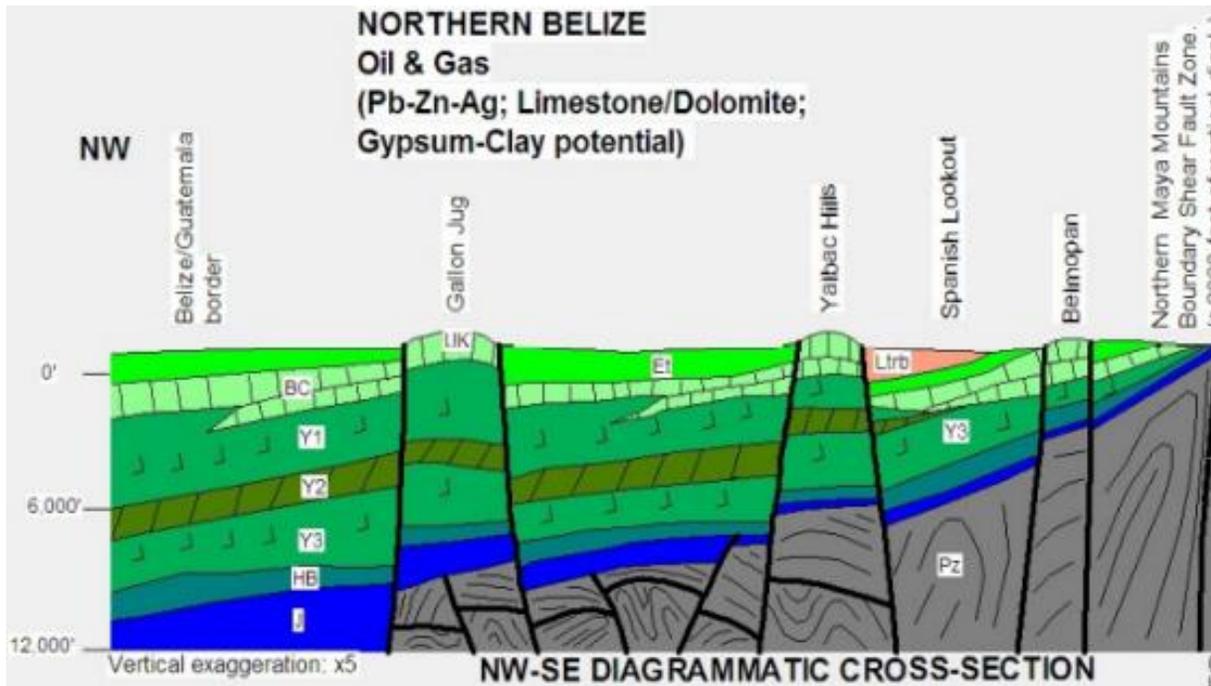


Figure A 1 Cross Section of Northern Lowlands

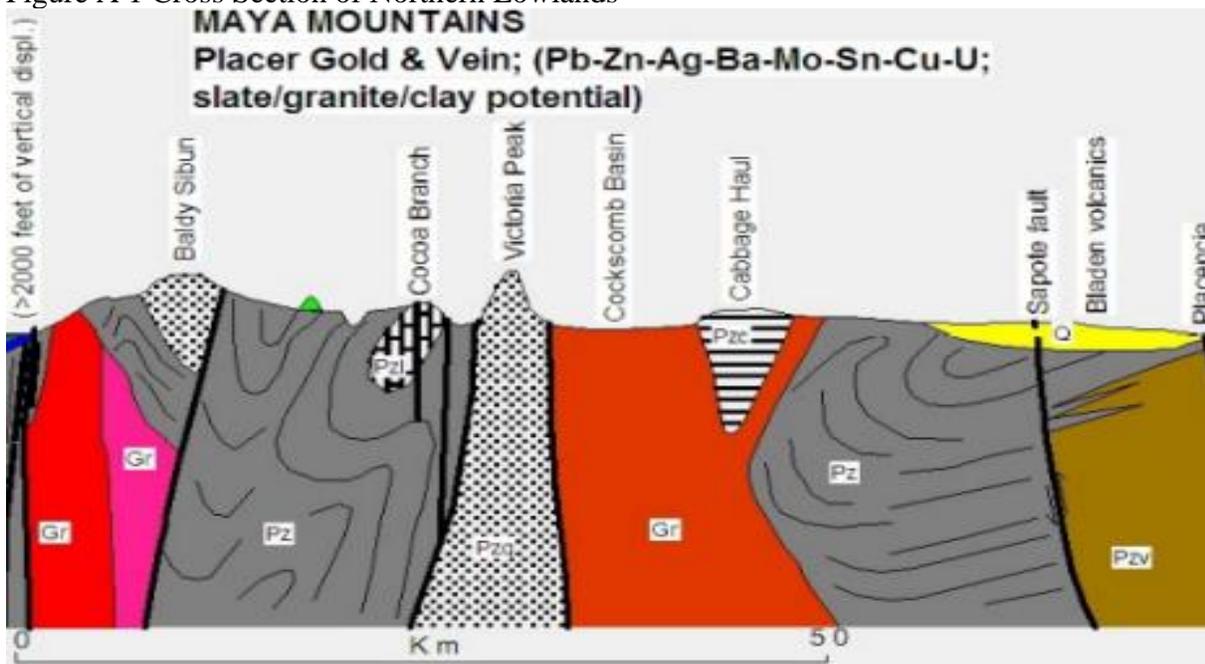


Figure A 2 Cross section of Maya Mountains

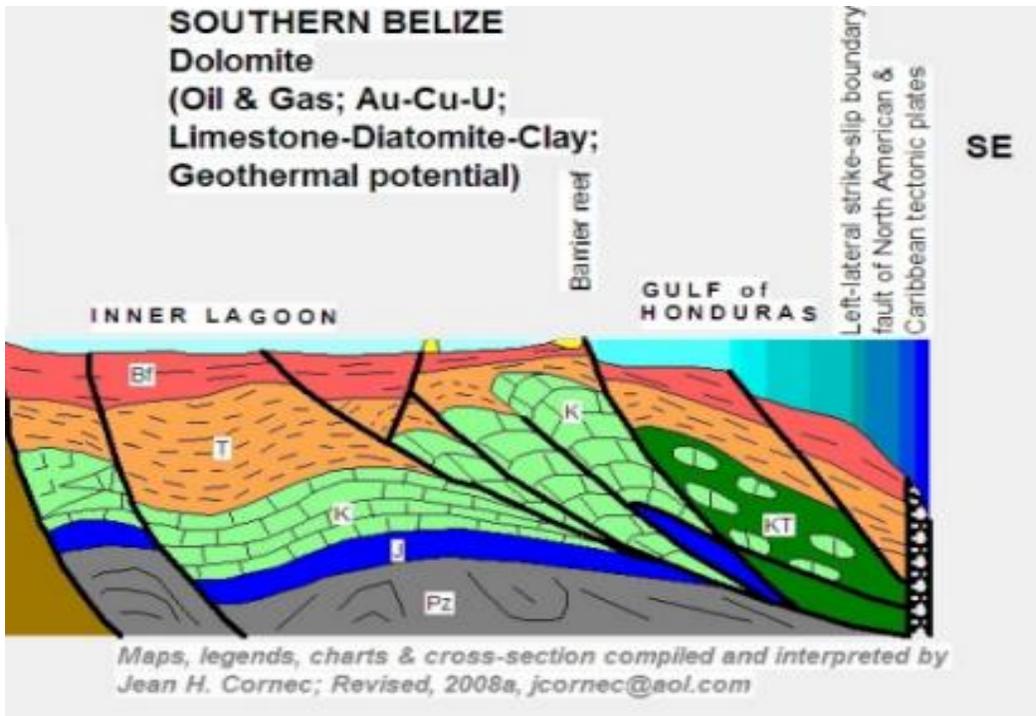


Figure A 3 Cross Section of the Southern Belize and its lowlands

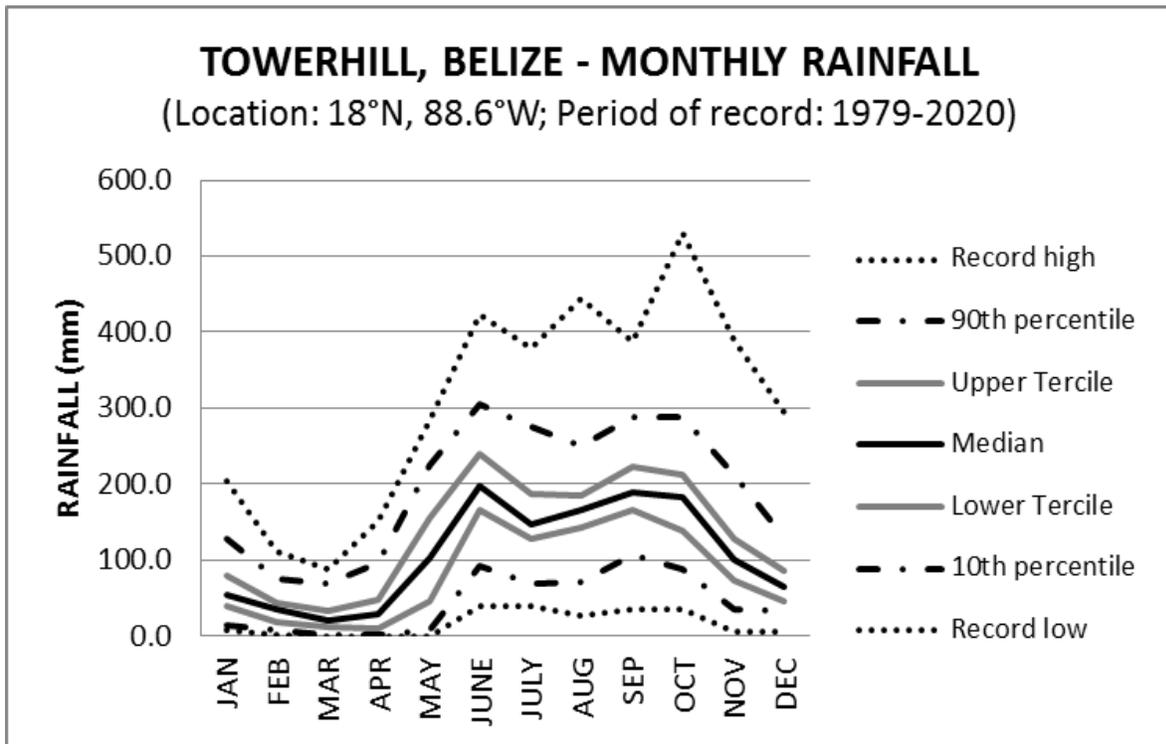


Figure A4 Monthly Rainfall in Townhill from 1979-2020

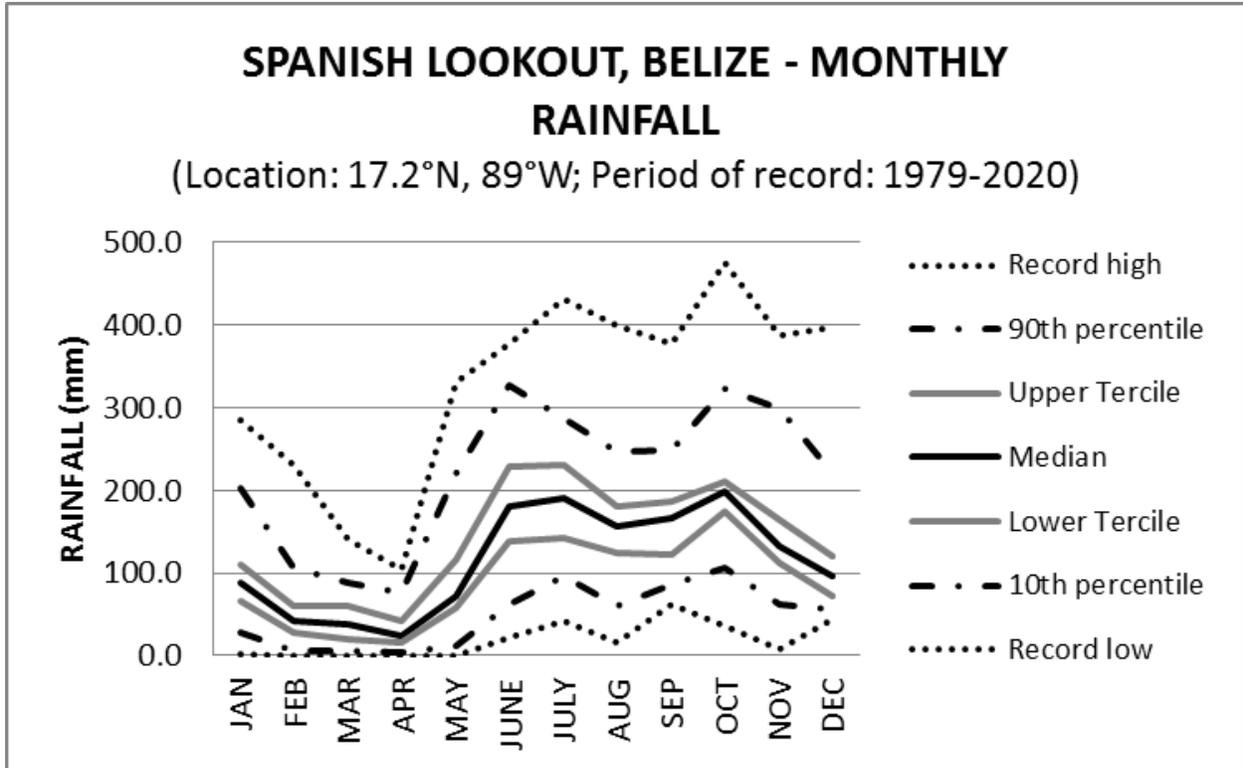


Figure A5 Monthly Rainfall in Spanish Lookout from 1979-2020

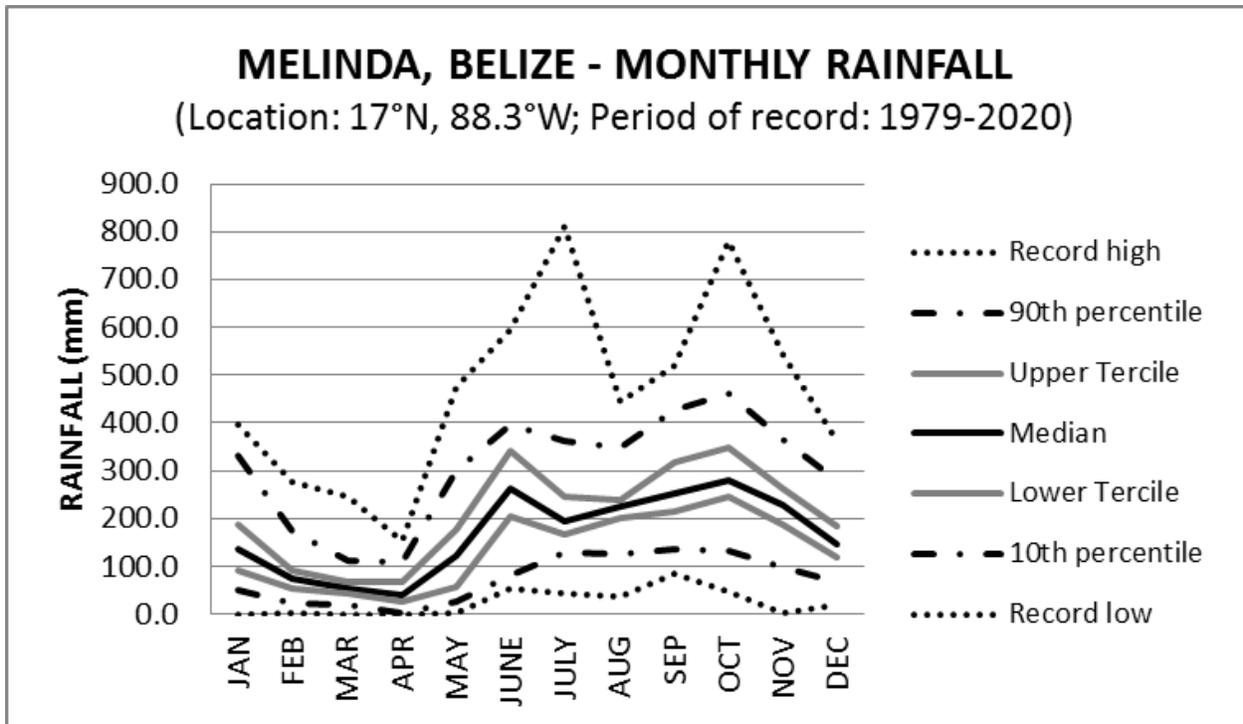
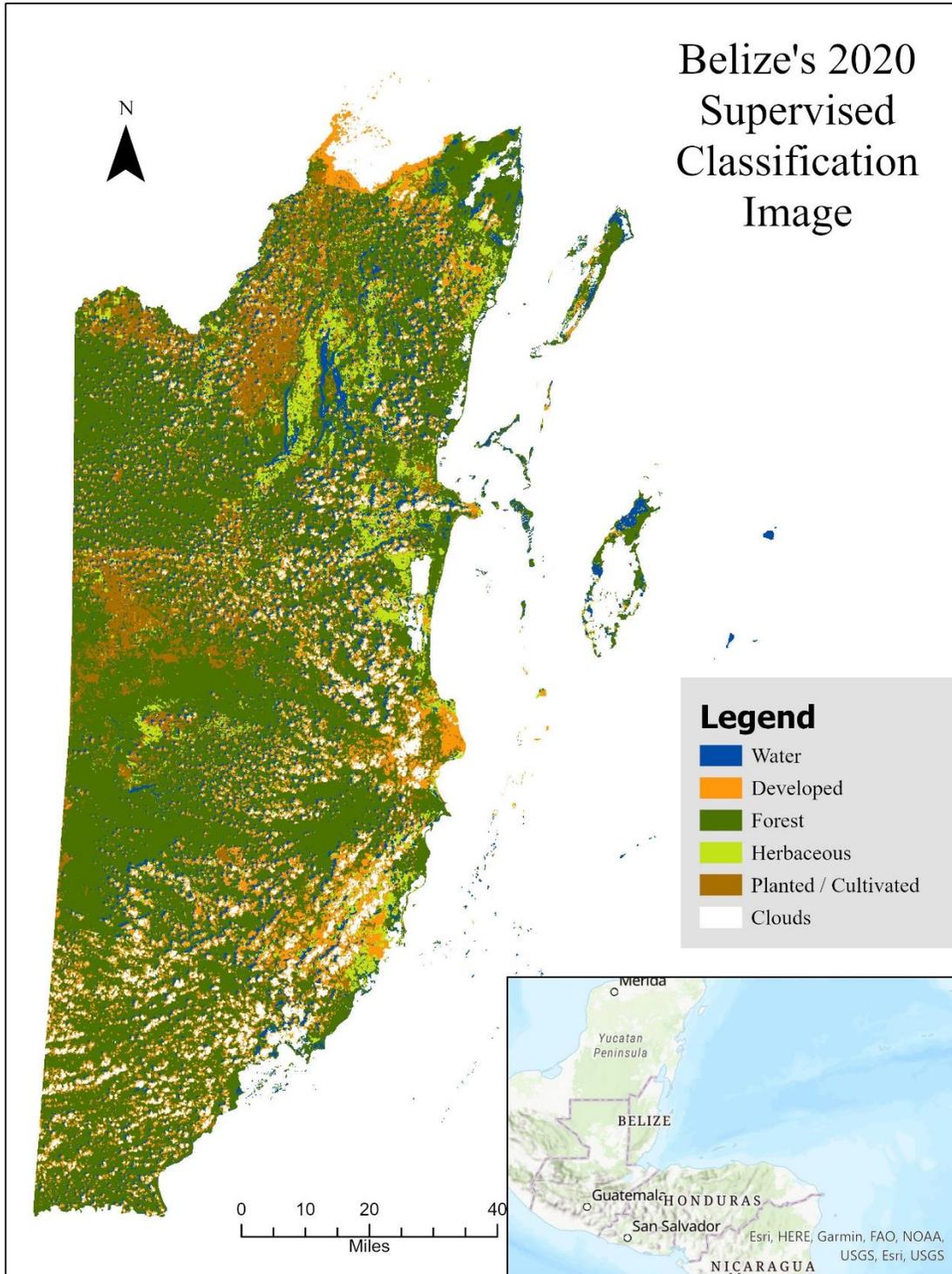
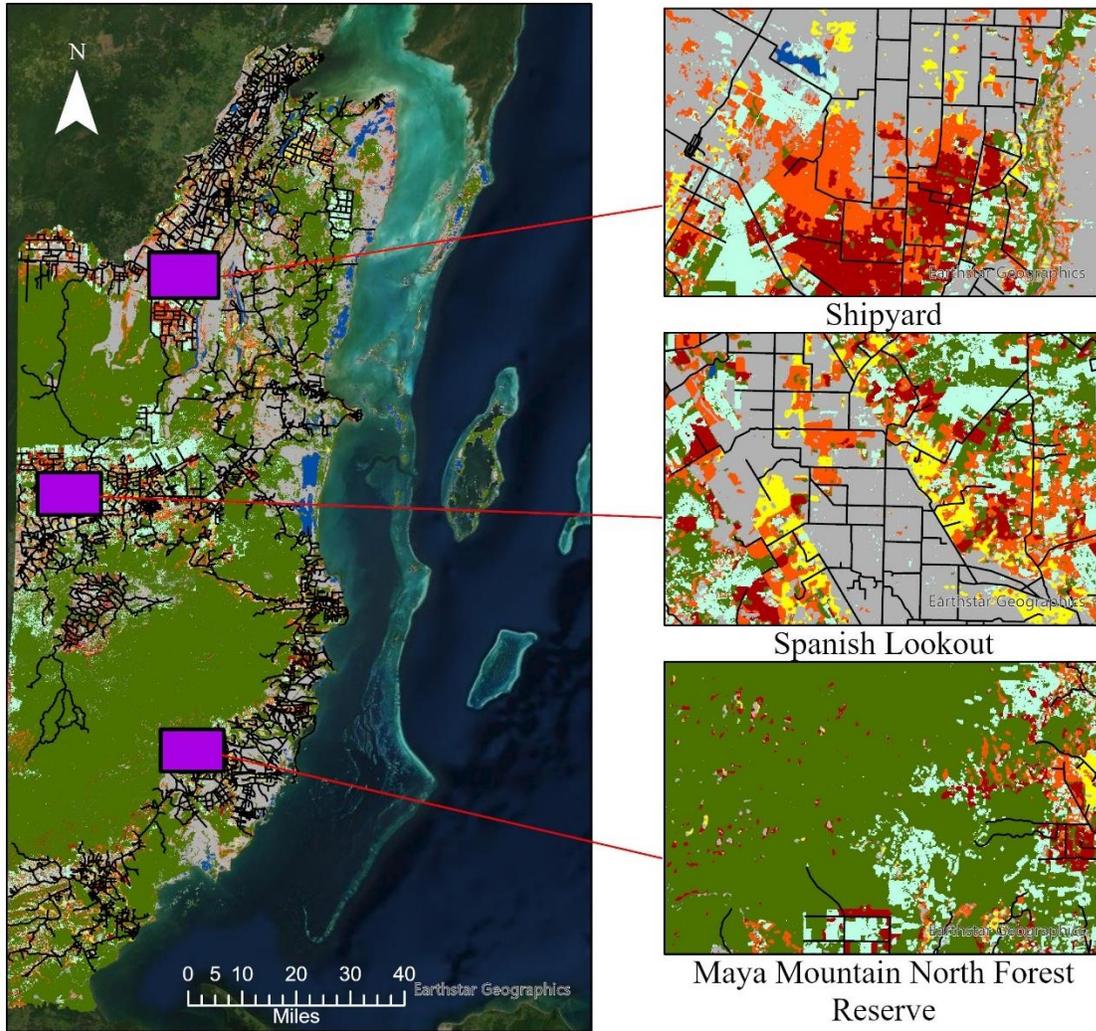


Figure A6 Monthly Rainfall in Melinda from 1979-2020

APPENDIX B: MAPS



Map 1 Supervised Classification of Belize



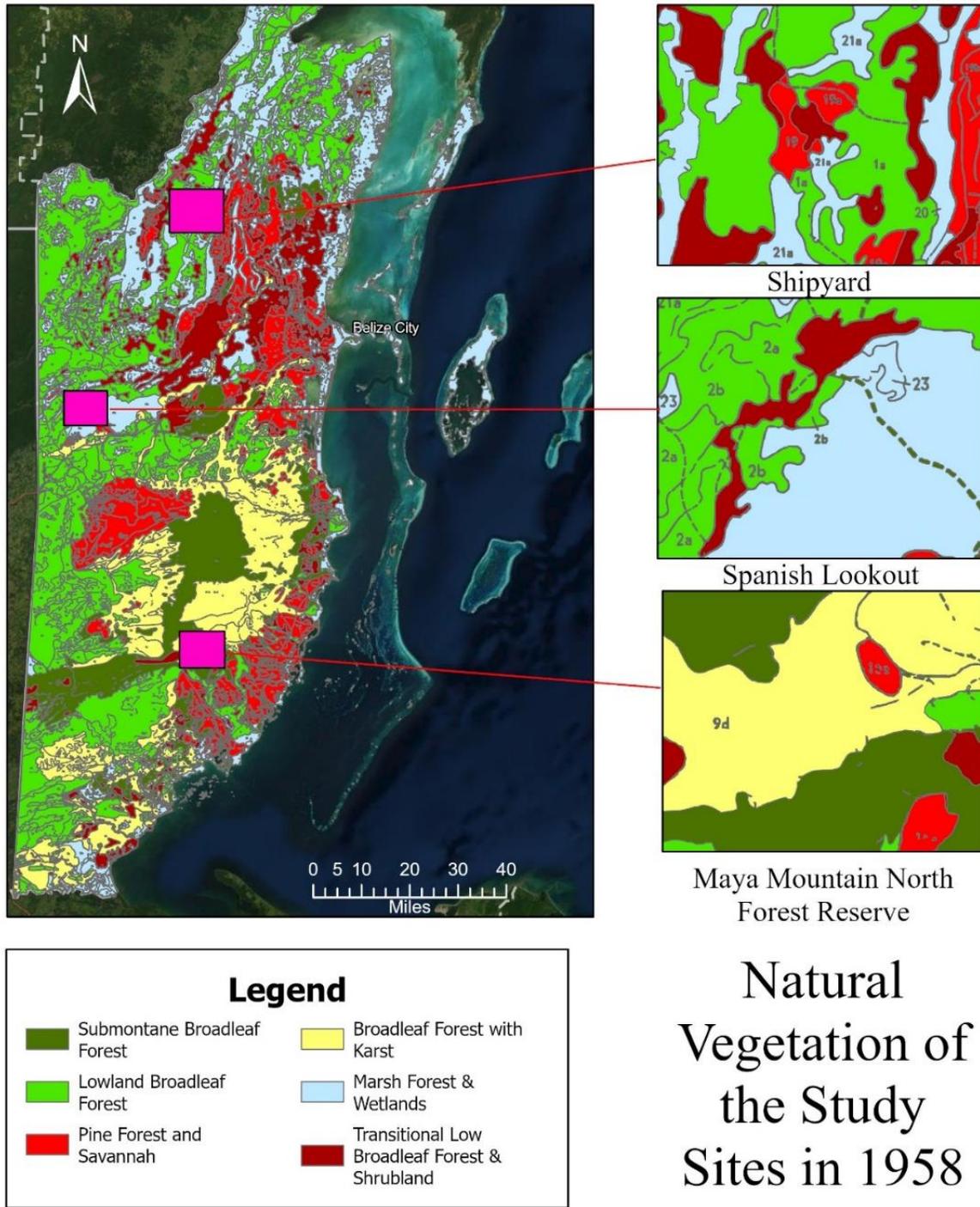
LEGEND

- Roads
- Water
- Forest
- Non-Forest
- Deforested 1980-1989
- Deforested 1989-2000
- Deforested 2000-2010
- Deforested 2011-2020

Belize Forest Cover Changes from 1980-2020

Credits: Cherrington, E. (2011). Belize Forest Cover Change: 1980-2010. ArcGIS Hub
AND
Source: Hansen/UMD/Google/USGS/NASA

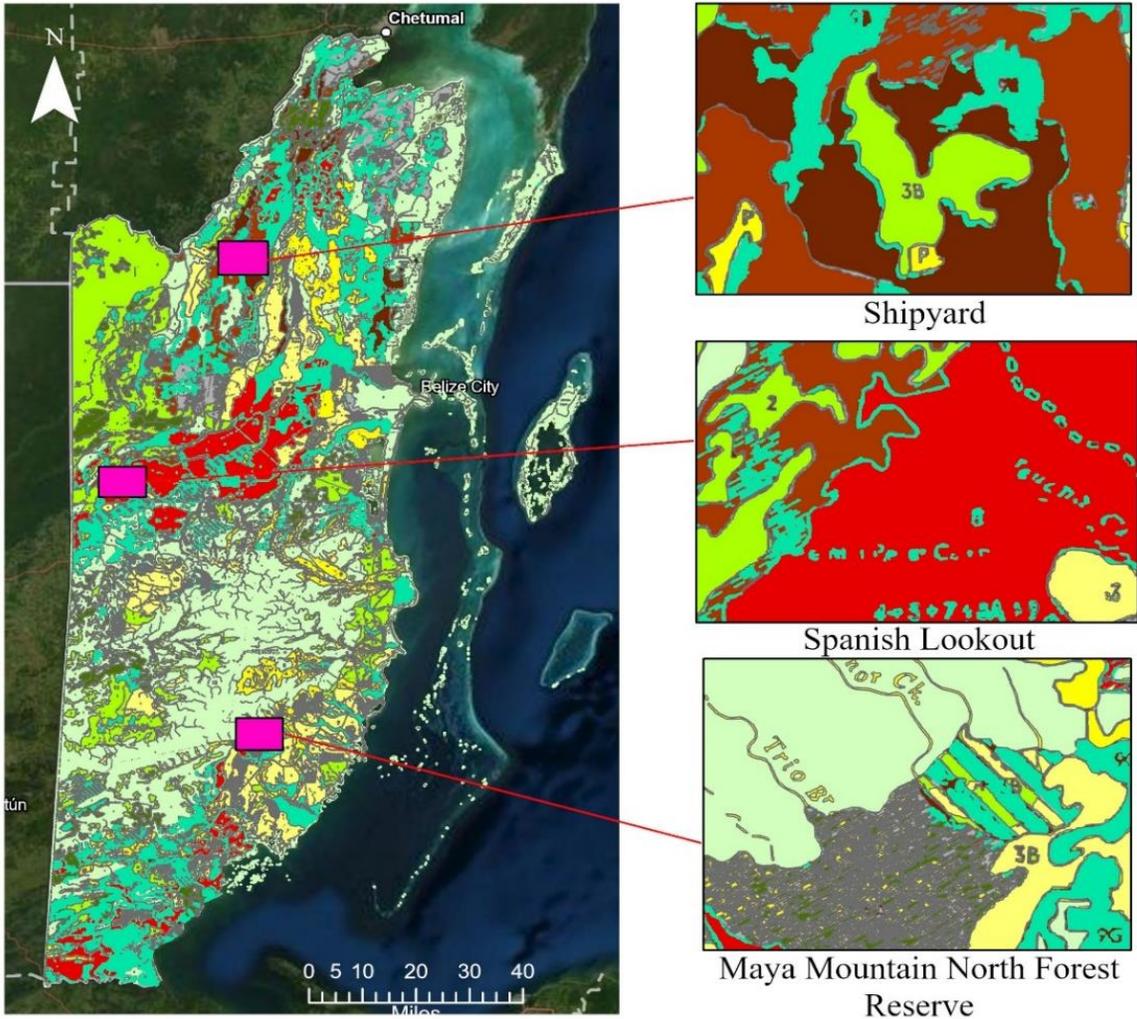
Map 2 Forest Cover Changes from 1980-2010 in Belize



Credits: Wright, A.C.S. et al. (1959). "Land in British Honduras." Colonial Research Publication No. 24.

Map 3 Belize's Natural Vegetation mapped by Wright et al 1959

Natural Vegetation of the Study Sites in 1958

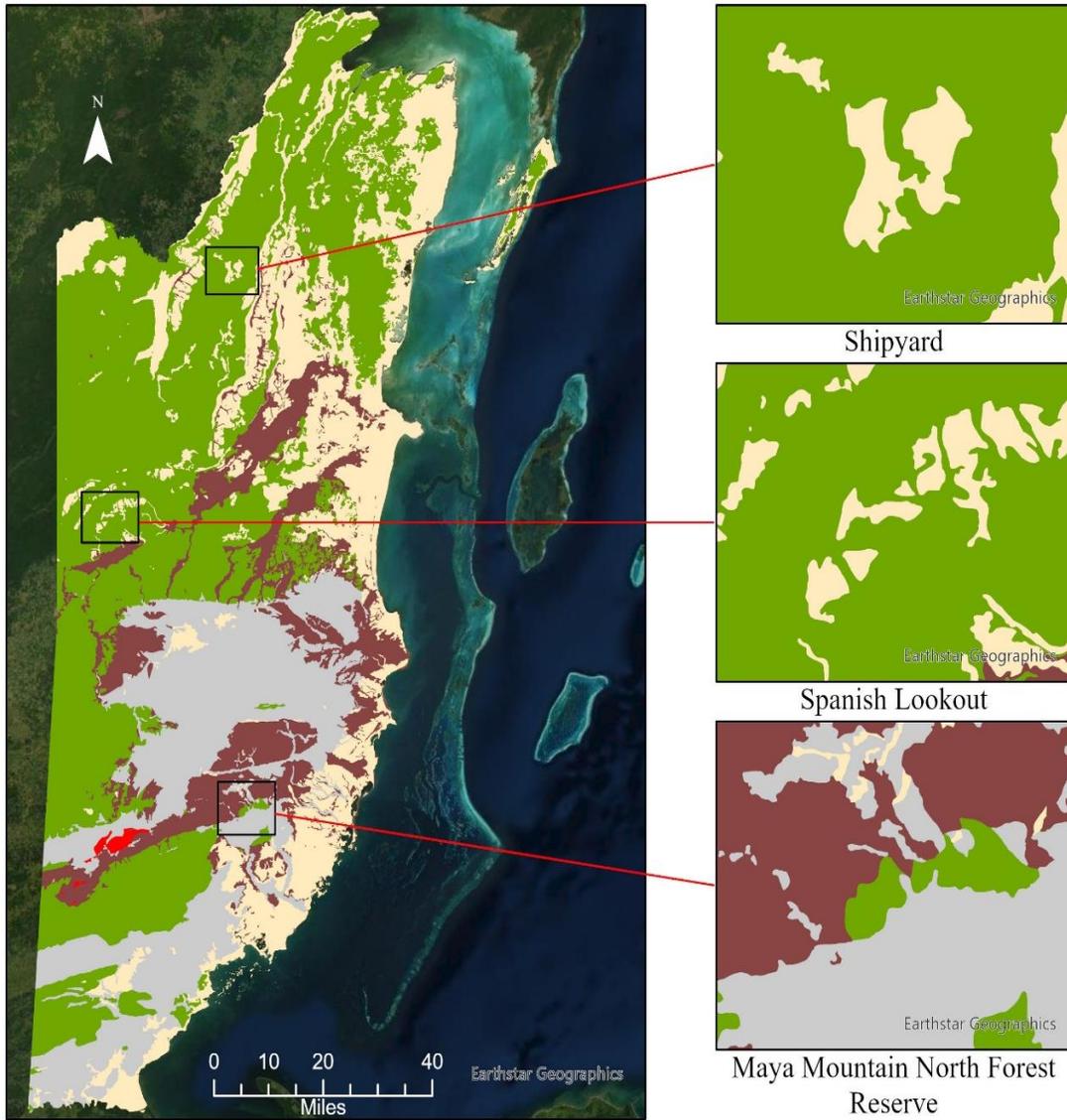


Legend	
 Protection Forest	 Short Rotation Pasture
 Long Rotation Pasture	 Sugar Cane
 Reafforestation (Mahogany Forest)	 Orchard Crops
 Short Arable Crop Rotation Land	 Sustainable Pine Forest Logging
 Orchard Crop W/in Pine Forest	 Pine Forest
	 Mahogany Forest

Potential Land Use of Study Sites by Charles Wright in 1959

Credits: Wright, A.C.S. et al. (1959). "Land in British Honduras." Colonial Research Publication No. 24.

Map 4 Belize's Potential Land Use (Wright et al., 1959)



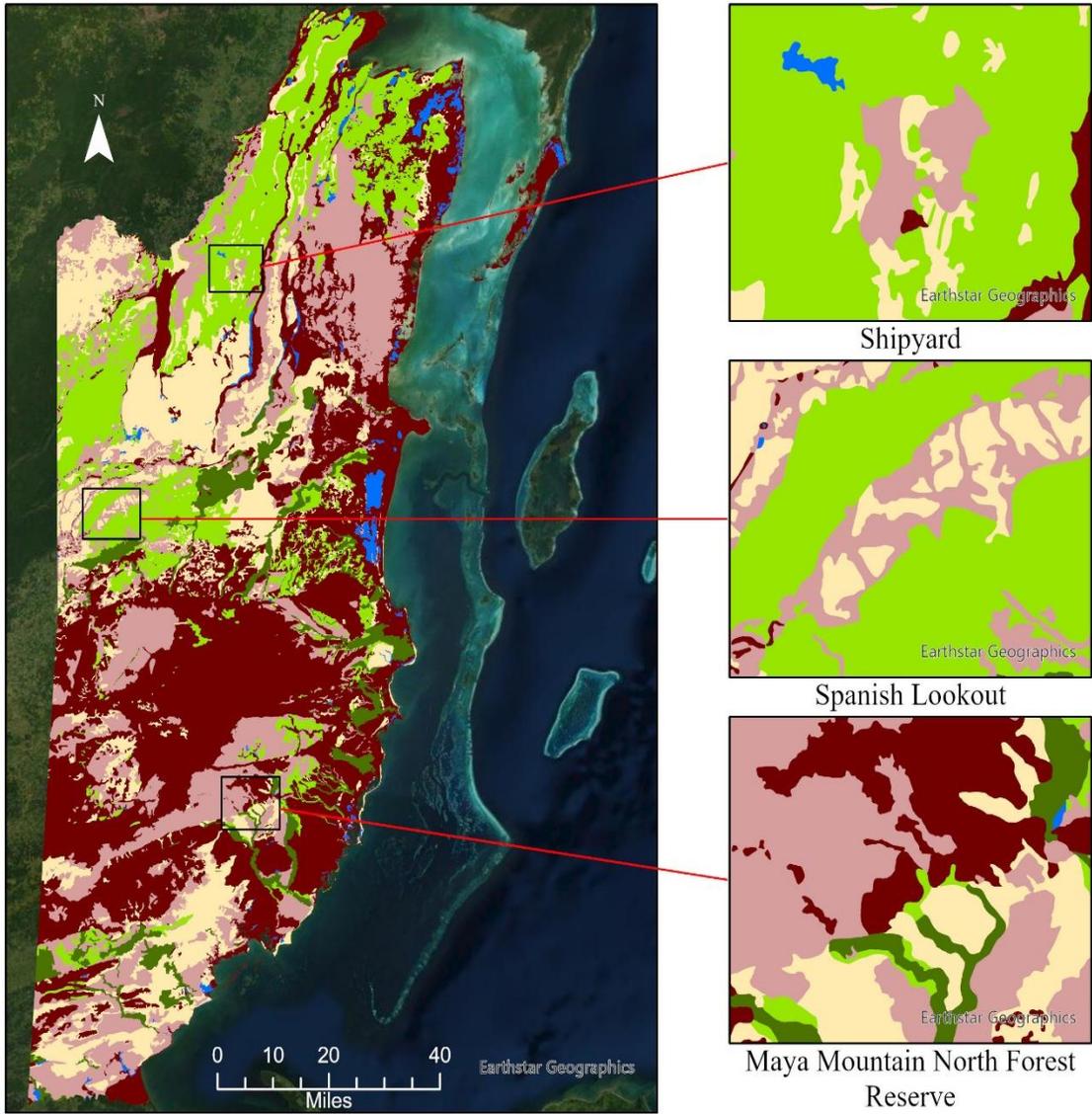
Legend

-  Alluvium
-  Granitic (acidic)
-  Limestone
-  Metasediments
-  Metavolcanic

**Geology of
Belize
(King et al. 1992)**

Credits: BTFS, King et al. (1992), Land Information Center, U.S. Geological Survey

Map 5 Geology Map of Belize



Agriculture Capacity

-  Water
-  1: High Chances for Financial Success
-  2: Good Chance of Success
-  3: Moderate Chance for Success
-  4: Marginal Chances for Success
-  5: Extremely Small Chances of Success

Agricultural Capacity by King et al. 1992

Credits: BTFS, King et al. (1992), Land Information Center, U.S. Geological Survey

Map 6 Agricultural Capacity of Belize