ABSTRACT

Mid-Summer Dry Spell and Agriculture in Jamaica:

Implications for farming practices, techniques and culture

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July 15, 2011

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At the beginning of the 21st century, Jamaica stands in a precarious situation which could have serious implications for the island's future. This stress may not have derived from a decrease in precipitation due to climate change, as well as a lack of interest in farming from smallholder farmers, which has become increasingly unsustainable. Younger Jamaicans have rejected farming as a career and instead opted for quick cash or migration out of the country in the hope of making their wealth elsewhere in the world. Thus, crop yields are at risk due to a smaller agricultural workforce. With decreasing labor rates and the current international economic crisis, the need for a high agricultural efficiency is greater than ever.

Annual yields are also affected climatologically by a mid-summer atmospheric phenomenon called the Mid-Summer Dry Spell (MSD), resulting in bimodal rainy seasons in April-June and August-November. Understanding how rainfall affects crop production is a primary goal of this research. To accomplish this, a three part analysis will be conducted utilizing correlations between rainfall and crop yield, mapping with Geographic Information Systems (GIS), and analysis of how the MSD impacts brightness, greenness and wetness of vegetation.

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

By

Sarah J. Jessop

July 15th, 2011

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Implications for farming practices, techniques and culture

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ACKNOWLEDGEMENTS

First I would like extend many thanks to my advisor, Dr. Scott Curtis for all his help and support on this journey. The many bumps and potholes in the road felt more like mountains and canyons, but with hard work, numerous questions, and countless meetings, I feel like I have completed a substantial piece of research that can really be put towards assisting the farmers of Jamaica.

I would also like to thank both Dr. Tom Crawford and Dr. Tom Allen for helping me learn many new facets of GIS and ERDAS. Even as one who is not entirely computer literate, it amazes me how much can be accomplished with these types of software. I hope to use my new found knowledge and put it to good use in the future.

My parents, John and Nancy Jessop, deserve recognition as well. They have raised three beautiful, talented and smart girls. Their love, support, and guidance helped me get to where I am today; an independent, hardworking, young woman. Every day I learn something new from them and I hope to keep doing so for a long time.

Last and certainly not least I would like to sincerely thank the love of my life, Terrence Munroe for keeping me sane, putting a smile on my face and a jump in my step throughout my two years here at East Carolina University. Without his love, support and willingness to provide help whenever it was needed, I most certainly would not have made it.

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Chapter 1: Introduction

Like many developing countries, Jamaica's primary source of income is dependent on agriculture. The agricultural sector is the largest employment sector, accounting for 39% of the labor force. Of the 2.7 million acres of land, 1.2 million are suitable for crops and pasture land. The majority of Jamaican farms are small (less than 5 acres) and located in the island's hilly interior. Despite their size, the small farms produce 80% to 90% of the country's domestic crops. They also produce a significant amount of export crops, including 68% of Jamaica's sugar, 59% of the citrus, 88% of the coffee and 62% of the cocoa (Woodsong 1994, 279-281).

At the beginning of the 21st century, Jamaica stands in a precarious situation which could have serious implications for the island's future. This stress arises from a decrease in precipitation due to climate change as well as a lack of interest in farming from smallholder farmers. Smallholder farming has become more and more unsustainable as younger Jamaicans do not prefer farming as a career. Instead, they either opt for quick cash or migrate out of the country in the hope of making their wealth elsewhere in the world. Thus, crop yields are at risk because of climate change and fewer farmers working the fields. With decreasing labor rates and the current international economic crisis, the need for a high agricultural efficiency is greater than ever.

The Mid-Summer Dry Spell (MSD) is an established atmospheric phenomenon that occurs throughout the Caribbean. Although it is not a true drought in the sense of near zero rainfall conditions, the MSD can result in as much as a 40% reduction in rainfall (Magaña et al. 1999, Small and Szoeke 2007). The consequence of this occurrence is a bimodal annual rainfall with a peak in May/June and a second greater maximum in October (Taylor and Alfaro 2005, Magaña et al. 1999).

It is the purpose of this study to make the spatial connection between localized climate (e.g. MSD), physical geography attributes and crop yield. It is the hope that the findings within this research can lead to more local research and will update technological development, farming practices, and policies in Jamaica.

The objective of this research is to understand how the MSD impacts crop growth in Jamaica, with a closer look in the parish of St. Elizabeth.

1) What is the effect of the MSD on the production of seasonal crops grown in Jamaica? How does the overall/seasonal crop production vary between 1965 and 2007?

2) Is there an optimal rainfall range for each crop within St. Elizabeth? Are there optimal locations within St. Elizabeth based on land-use and optimal rainfall ranges?

3) What are the impacts of the MSD on the vegetation within St. Elizabeth?

Chapter 2: Literature Review

Agriculture in Jamaica

Jamaican farmers have been tilling the land for hundreds of years, and know the environment better than anyone. It is important to note how Jamaican farmers perceive the MSD and climate change, and the techniques and innovations they use in order to deal with drought. Jamaican farmers also comment on how they perceive the changing times regarding the youth. Understanding the human connection to drought is vital in mitigation and adaptation strategies.

Perceptions

The human connection begins with how local Jamaicans view their current standing within the farming sector**.** It is important to note that these perceptions should be viewed only as a background to underlying issues within farming communities. Cynthia Woodsong (1994) states that there is concern that the rural concentration of elders may have negative consequences for agricultural production. Since the 1940s, the average age of farmers in Jamaica has hovered around the early 50s. Understanding the elderly population's role in agricultural production is important because there may be implications for the well-being of older farmers as well as the national agricultural sector. Woodsong argues that agricultural development and the situation of older farmers could be improved by addressing three issues: (1) although young adults generally do not enter into fulltime farming, many eventually do become farmers. Until then, they may be involved in agricultural activities that are 'invisible'; (2) Older farmers have a 20 year or more career of full-time farming ahead of them, which is a period of time deserving appropriate consideration in agricultural policy; (3) In Jamaica, economic options and formal arrangements for old age care are limited; participation in the agricultural economy substitutes for retirement (1994, 277-278).

In America, the stereotypical farming family owns hundreds of acres of farm land and passes down farming techniques to their children and their children's' children; keeping the farm within the family. Children learn how to run the farm from an early age, learning the tricks of the trade and taking over once their parents retire. Although in Jamaica, this is not true in most cases. There is a general trend of the Jamaican youth being lethargic and highly uninterested in farming. Weis (2006) examines the crisis of the Jamaican peasantry, who are struggling against pressures old and new. He states that as there is a need and possible opening to revitalize agriculture, there are many young people who are rejecting farming. Weis also believes that there are some very destructive social currents at work, weakening the pressure for change.

In order to understand the current conditions and future possibilities, Weis (2006) conducted qualitative interviews of 43 farmers within the parish of St. Mary located in north-eastern Jamaica. To better describe the demise of the farming culture, one farmer noted that: "most young people don't know de moon no more" (Weis 2006, 80) in other words, they do not understand how lunar cycles guide planting. Many of those who participated in the interview process blamed young people's rejection of farming on their 'laziness' and lack of work ethic. This idea is best summarized by one old farmer in his assertion that "young people in Jamaica don't love to farm…Dem weak and full of violence…laziness is a disease" (Weis 2006, 80).

This laziness and lack of farming corresponds to a rise in banditry. This stems from the younger generations who are impatient and unwilling to invest time and labor for a long-term payoff and are more interested in finding a source for quick money. In order to get a clearer picture of the social issues as they relate to crop production, more research would need to be conducted. For the purpose of this study, this information should only be taken as background of the situation currently unfolding on the island.

Local knowledge

Local knowledge of farming is important**,** especially on small farms located in areas of the world where agriculture is one of the main sources of income. Beckford and Barker (2007:119) describe local knowledge as "dynamic . . . [it] allows people to carry out their daily tasks as well as adapt and cope with new problems in the face of environmental and economic uncertainties and hardships". Locals use their own knowledge as well as limited resources in order to have a productive year. This leads to the question of how drought and climate change might be perceived by the local Jamaicans.

A study was recently completed (Gamble et al., 2010) in order to reach a better understanding of drought and climate change in southwestern Jamaica. A survey of sixty farmers in the St. Elizabeth Parish was taken in order to investigate local knowledge and perception of drought. It was determined that the farmer perception of drought is not driven only by magnitude and frequency of dry months, but also by the difference between seasons. Farmers notice oscillation between a dry early season and wet primary season just as they do persistent dry conditions. Thus, Gamble et al. determined that any development of drought adaptation and mitigation plans must not focus just on drought, but it should compare moisture conditions between seasons, including the total range between wet and dry seasons (16-17).

Adaptation

To contend with climate and economic issues, small scale farmers have needed to adapt innovative survival strategies in order to maintain their crop yield and income. Several of these innovations include grass mulching, kitchen gardens, and farm fragmentation. Beckford et al (2007) elaborate on these innovations in their paper which highlights these adaptive practices in both the parish of Trelawny, responsible for 40 percent of the Jamaica's yams, and the parish of

St. Elizabeth, which has been consistently among the highest producers of domestic crops in the last 20 years.

Since the parish of St. Elizabeth is located in the rain shadow, devastating droughts are common. This has led many farmers to design a drip irrigation system which is hooked up to their domestic water supply. Most farmers end up purchasing water and storing it in containers on their field and use small water cans to manually water individual plants. This is a time consuming laborious method, but one that makes efficient use of scarce water resources. A unique local technique uses grass mulch in order to aid moisture retention and keep weeds down. After land is prepared for planting, the ground is then covered with dried grass for the duration of the growing season. In some cases, some farmers have stopped producing food crops in order to grow this grass, as it has become a profitable cash crop. This technique is not new by any means; it has been practiced for as long as the oldest resident in the area can remember (Beckford et al. 2007, 279).

Kitchen gardening provides the space needed to perform many different tasks for families in Jamaica. The first being sustainable production. These gardens are a good example of space used wisely around homes, usually able to hold as many as 60 plant species. These plants could be grown specifically for family consumption, or to make a little extra income. Thomasson (2004) describes the present day Caribbean kitchen gardens as adaptive survival strategy among resource poor, small scale farmers and concludes that kitchen gardens are an environmentally sustainable agricultural system functioning with minimal external inputs, support and infrastructure. Another important use of kitchen gardens is as a site for experimentation. Kitchen gardens are used as training grounds for children within farming communities where they can gain knowledge of farming (Beckford et al. 2007, 281-282).

Another innovation used is known as farm fragmentation, which can be easily observed throughout all of the Caribbean. This is a technique where farmers acquire plots over a wide area, resulting in a random spatial pattern of plots, and is usually the result of farmers being unable to procure an adequate amount of land in a single parcel. Farm fragmentation is also a useful tool when a farmer is interested in certain soil conditions or microclimates in order to grow their crops. In the parish of Trelawny, between 2000 and 2002, 37 percent of all farmers used the technique of fragmentation (Beckford et al. 2007, 281-282).

Other actions, mentioned by Gamble et al. (2010) that can assist in adaptation to climate change in drought in Jamaica and the Caribbean include: refinement of downscaling techniques to appropriately assign climate data bases to specific locations; a more in-depth analysis of farmer experience in forecasting and adaptation to specific drought events; a better understanding of how government policy and socio economic forces intersect with environmental change; and development of end-user focused drought management products.

Knowledge from local farmers, including individual understandings of climate change and weather fluctuations, as well as how to react to these alterations, are important for those whose livelihoods depend on the crop yield. Understanding the current issues and possible future problems could lead to an adaptation of local and small farm cultivator's knowledge on a greater scale for the success of the country.

Climate of Caribbean

The climate of the Caribbean islands is characterized by distinct dry and wet seasons with orography and elevation being significant modifiers on the sub-regional scale. Dominant influences include the North Atlantic Sub-tropical High (NASH) and ENSO. During the winter in the Northern Hemisphere, the NASH lies further south. During this time, the region is generally at its driest due to the strong easterly trade winds, a strong inversion, a cool ocean and reduced atmospheric humidity. As spring sets in, the NASH moves northwards, decreasing trade wind intensity. Thus, the region comes under the influence of the equatorial trough (Mimura et al., 2007).

In a recent study Jury (2011), the long term variability and trends in the Caribbean Sea were examined. The key question asked was how the global warming signal was reflected in the Caribbean Sea. In order to help answer this question, several biophysical relationships were examined including annual marine catch for the Caribbean Sea and annual crop yield for all the countries in the Caribbean. The study determined that the Caribbean crop yield followed rainfall until recently; a weak drying trend can be seen (Figure 1). It was determined that crop yield is less sensitive to upper ocean conditions.

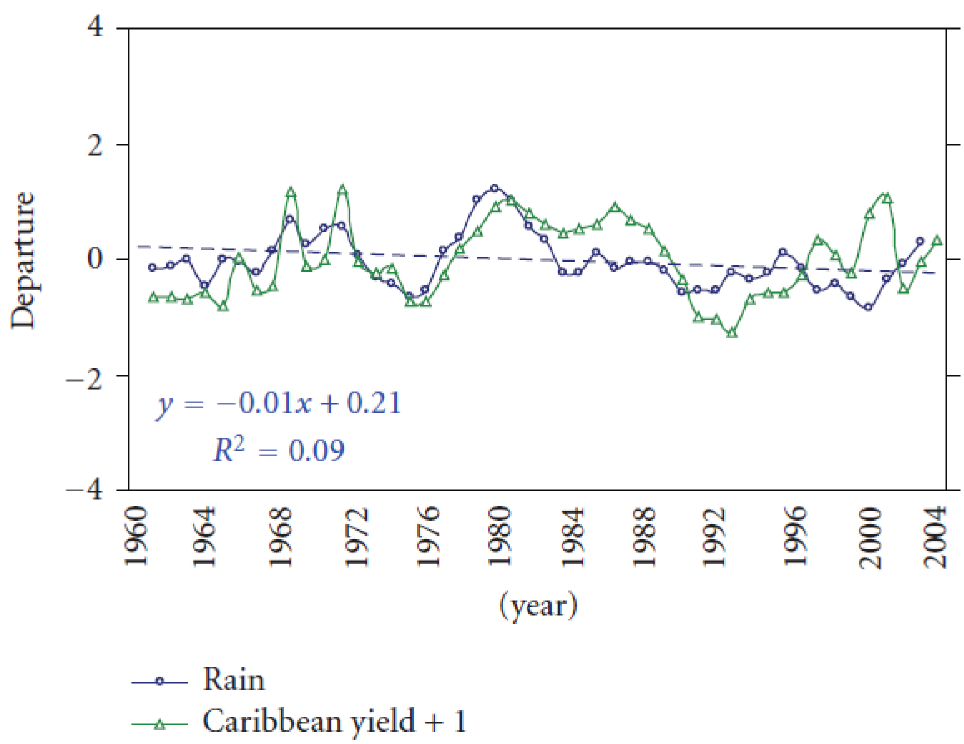


Figure 1. Caribbean crop yield lagged by 1-yr and smoothed rainfall with trend, taken from Jury 2011 (Figure 6b).

Temperature

Temperatures in the Caribbean remain fairly constant throughout the year with a small annual range of about 2-7°C. On average, temperatures usually increase from May and peak in the upper 20s Celsius in August and September. During the winter and early spring (December to April), temperatures are coolest generally in the lower 20s near sea level (Taylor and Alfaro 2005). Extreme temperatures are rare in the Caribbean due to the moderating effects of the sea, and the very high level of evapotranspiration. The hottest month immediately precedes the onset of the rainy season, with the period of greatest warmth occurring during the wet season. This occurs since cloud cover and high atmospheric humidity accentuate the greenhouse effect at the same time that increased day length makes for slightly longer periods of global radiation and heating (Granger, 1985).

Precipitation

The islands of the Caribbean vary in size, shape, topography and orientation. All of which play a role in the amount of rainfall received by the individual islands. Jamaica is considered one of the larger and more mountainous islands within the Caribbean, along with Cuba, Hispaniola and Puerto Rico. These islands receive approximately 160cm of rainfall a year, with 500cm on the highest peaks. More specifically, a transect across the mountains of Jamaica from north to south along 76 25' W shows an increase in mean annual rainfall from 3000mm on the north coast, to 8000mm at the crest decreasing again to 1800mm on the southeast coast. It is due to the rain shadow which is located on the southern coasts, that there are noticeably arid conditions in this region. It is evident that precipitation distribution in the Caribbean has spatial and temporal influences operating on it (Taylor and Alfaro 2005, Granger 1985).

Mid-Summer Dry Spell

The Caribbean MSD reaches a maximum in the vicinity of Jamaica, Cuba and the Yucatan peninsula, and becomes stronger and more significant from east to west (Curtis and Gamble, 2008). These authors identified several forcing mechanisms which may contribute to the above spatial variability: (1) an uneven expansion or riding of the North Atlantic Subtropical High (NASH) into the Caribbean; (2) localized increase in pressure (enhancing the strength of the MSD) and; (3) the changing surface wind during the summer months.

The MSD occurs in other areas around the world. The Mexico and Central American MSD has precipitation peeking in during June and September-October and a minimum in July and August (Magaña et al., 1999). The authors concluded that there is a great socioeconomic importance of the MSD; therefore more research would need to be conducted in order to develop a prediction scheme to determine the onset, intensity and length.

The Central American MSD was also discussed by Small and Szoeke (2007) who aimed to describe the regional characteristics of MSD and propose possible forcing mechanisms. More specifically, they investigated the importance of seasonal changes in the Pacific ITCZ and of the Atlantic subtropical high to the development and decay of the Central American MSD.

Understanding how the MSD impacts vegetation in the Caribbean is an important step in understanding how agricultural production in Jamaica is affected. An excellent method to do so is to utilize the Normalized Difference Vegetation Index (NDVI). The NDVI is defined as the ratio between the difference of the reflectance in the near-infrared and red wavelengths to the sum of the two and is commonly used to assess vegetation vigor**.** Singh et al. (2003) converted NVDI into two indices, the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) using Advanced Very High Resolution Radiometer (AVHRR). Both indices were used in order to estimate vegetation health and monitoring drought in India. In the months of June, July, August and September, the VCI variations indicate that the crop is stressed and conditions for drought have developed. Low TCI values were also found during June and July, concurrently, crop data showed a decrease in yield. By and large, VCI and TCI can be used for drought detection and mapping.

In a recent study conducted by Allen et al. (2010), the NDVI was used to assess the impact of the MSD and to catalog its intensity as seen through vegetative response within the "bread-basket" region of an Intra-American Sea (IAS) island nation. They found that the spatial variation of MSD related to NVDI is detected by computing an NDVI percent difference between points that represent a decline in vegetative vigor in mid-summer. They concluded that there was an average 17% reduction in NDVI associated with the MSD between 2001 and 2007. It should also be noted that spatially, there is a difference between parishes. For instance, since St. Elizabeth sits in the rain shadow of Jamaica, it is relatively dry. Further, northern St. Elizabeth is positioned in a fertile region dominated by large scale commercial agriculture, while in southern St. Elizabeth, small scale farms exist on the steep slopes with less favorable soil and limited irrigation, which fuels the already high vegetative stress levels during the MSD. Other impacts during the MSD include reduced cloud coverage and increased surface heating; all of which can negatively impact vegetation within the region, resulting in crop failure and agricultural stress (Allen et al. 2010).

Climate Change in the Caribbean

Understanding how climate is changing in the Caribbean is important in understanding the current state. The small islands of the Caribbean have characteristics which make them vulnerable to effects of climate change, sea-level rise and extreme events. The 4^{th} annual report of the Intergovernmental Panel on Climate Change describes general features, observed trends, and future trends of climate and weather for small islands within the Caribbean.

Climates of small islands are variable, generally characterized by large seasonal precipitation differences in low-latitude islands and large seasonal temperature differences in high-latitude islands. Tropical islands also experience cyclones and other extreme climate and weather events, causing considerable loss to life and property (Mimura et al., 2007).

Observed Trends

In the Caribbean, analyses shows warming ranged from 0 to 0.5^{O}C. The percentage of days having very warm maximum or minimum temperatures has increased considerably since the 1950s, while the percentage of days with cold temperatures has decreased. The maximum number of consecutive dry days is decreasing and the number of heavy rainfall events is increasing. Hurricane activity was greater from the 1930s to the 1960s, in comparison with the 1970s and 1980s and the first half of the 1990s. Beginning in 1995, all but two Atlantic hurricane seasons have been above normal. Those two seasons occurred during the two El Nino years, 1997 and 2002. El Nino acts to reduce activity while La Nina acts to increase activity in the North Atlantic. The Caribbean region has also experienced, on average, a mean relative sea-level rise of 1 mm/yr during the 20^{th} century. Regional variations were also observed, due to large scale oceanographic phenomena such as El Nino and volcanic and tectonic motions (Mimura et al., 2007).

Future Trends

<u>Temperature and Precipitation</u>

The IPCC warns that the projections on temperature apply for the most part, to open ocean surfaces and not to land surfaces. Thus, temperature changes may be higher than current projections. Seven coupled atmosphere-ocean general circulation models (AOGCMs) were used with greenhouse gas and aerosol forcing to create projected changes in seasonal air surface temperature (Table 1) and precipitation (Table 2) for three 30-year periods. All seven models projected increased surface air temperature for all regions of the small islands (Mimura et al., 2007).

Figure 2 shows that the annual mean precipitation decrease is spread across the entire region. In December-January-February (DJF), some areas of increases are noted and in June-July-August (JJA), the region-wide decrease is enhanced, especially over the Greater Antilles. Figure 3 illustrates the regional averages of temperature and precipitation projections from a set of 21 global models in the Caribbean per season. It can be seen that temperatures rise consistent with the global mean, while precipitation on the other hand decreases significantly; especially during the period from June-August (Christensen et al., 2007).

Table 1. Projected increase in air temperature (^{o}C) by region, relative to the 1961-1990 period (IPCC).

Region	2010–2039	2040–2069	2040–2069
Mediterranean	0.60 to 2.19	0.81 to 3.85	1.20 to 7.07
Caribbean	0.48 to 1.06	0.79 to 2.45	0.94 to 4.18
Indian Ocean	0.51 to 0.98	0.84 to 2.10	1.05 to 3.77
Northern Pacific	0.49 to 1.13	0.81 to 2.48	1.00 to 4.17
Southern Pacific	0.45 to 0.82	0.80 to 1.79	0.99 to 3.11

Table 2. Projected change in precipitation (%) by region, relative to the 1961-1990 period (IPCC).

Region	2010–2039	2040–2069	2040–2069
Mediterranean	–35.6 to +55.1	–52.6 to +38.3	–61.0 to +6.2
Caribbean	–14.2 to +13.7	–36.3 to +34.2	–49.3 to +28.9
Indian Ocean	–5.4 to +6.0	–6.9 to +12.4	–9.8 to +14.7
Northern Pacific	–6.3 to +9.1	–19.2 to +21.3	–2.7 to +25.8
Southern Pacific	–3. 9 to +3.4	–8.23 to +6.7	–14.0 to +14.6

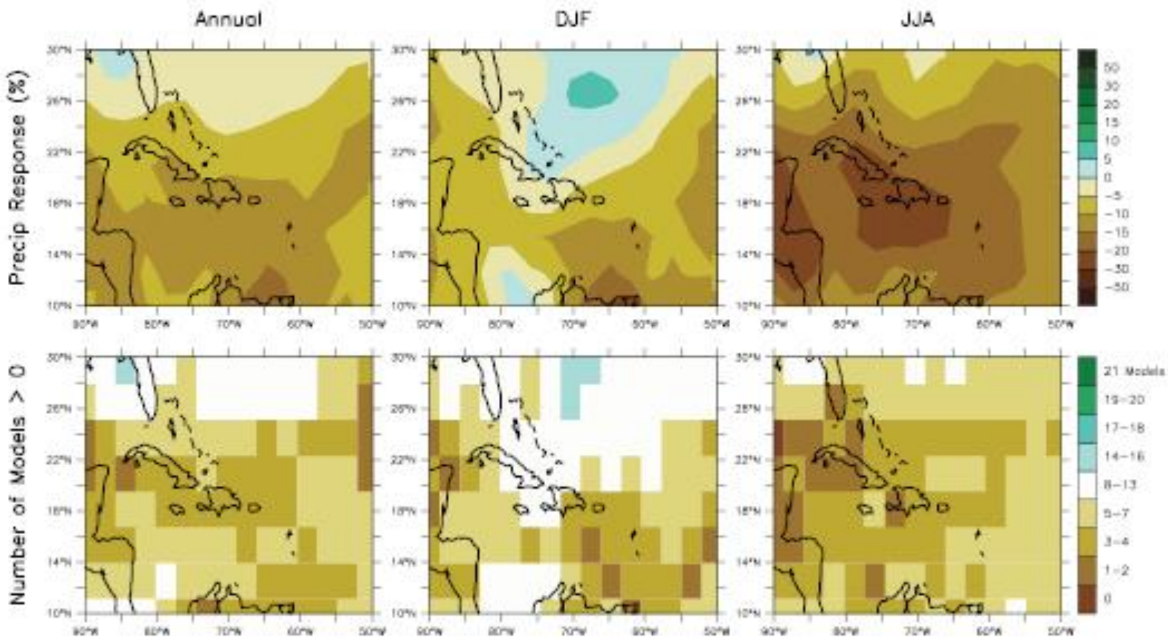


Figure 2. Precipitation changes over the Caribbean (IPCC).

Region[a]	Season	Temperature Response (°C) Min	25	50	75	Max	T yrs	Precipitation Response (%) Min	25	50	75	Max	T yrs	Extreme Seasons (%) Warm	Wet	Dry
SMALL ISLANDS																
CAR	DJF	1.4	1.8	2.1	2.4	3.2	10	-21	-11	-6	0	10		**100**	2	
	MAM	1.3	1.8	2.2	2.4	3.2	10	-28	-20	-13	-6	6	>100	**100**	3	**18**
10N,85W	JJA	1.3	1.8	2.0	2.4	3.2	10	-57	-35	-20	-6	8	60	**100**	2	**40**
to	SON	1.6	1.9	2.0	2.5	3.4	10	-38	-18	-6	1	19		**100**		**22**
25N,60W	Annual	1.4	1.8	2.0	2.4	3.2	10	-39	-19	-12	-3	11	60	**100**	3	**39**

Figure 3. Projected temperature and precipitation changes (IPCC).

Global climate models (GCMs) are one of the most common tools for investigating climate change and making projections for the future. However, the resolution of global models is too coarse to provide information at local and regional scales for assessments and the development of local adaptation strategies. This is particularly true for the Caribbean because most of the small islands aren't represented in the GCMs. In order to understand future climate of the Caribbean, version 1.3 of the Hadley Center's regional climate modeling system-PRECIS was used; which is a dynamical downscaling atmospheric and land surface model (Campbell et al., 2010).

Annual and seasonal projections were conducted for precipitation and temperature for 2071-2100. Annual rainfall is expected to decrease for much the Caribbean. The decrease ranges from 25-50%, with the largest decrease over the Lesser Antilles and the Central Caribbean basin, including Jamaica and Puerto Rico. Seasonal rainfall indicates a wetter north and a drier south Caribbean during the dry season NDJ and FMA. The projections also indicate up to a 75% increase over the northern Caribbean. A drier Caribbean is also noticeable during MJJ and ASO between 2071 and 2100 (Campbell et al., 2010).

Annual temperatures are projected to increase over the Caribbean, by 2-5^{o}C. The larger islands, i.e. Cuba, Jamaica and Hispaniola exhibit the greatest warming. Seasonal projected temperatures also indicate an increase in temperatures across the Caribbean. Warming will be strongest over land, particularly Cuba, Jamaica, Hispaniola, Central America and northern South America, by 2-5^{o}C (Campbell et al., 2010).

Sea-Level

It is globally projected that the averaged sea-level rise at the end of the 21st century will range from 0.19 to 0.58 m. Climate models also indicate geographical variation of sea-level rise due to non-uniform distribution of temperature and salinity and changes in ocean circulation. Other regional variations include island tectonic setting and postglacial isostatic adjustment (Mimura et al., 2007).

Extreme Events

Although there has yet to be any solid evidence in the observed record of changes in tropical cyclone behavior, recent model results show an increased peak in wind speed and increased mean and peak precipitation intensities. Maximum tropical cyclone wind intensities could increase, by 5 to 10% by around 2050. The number of intense cyclones is likely to increase although the total number may decrease on a global scale (Mimura et al., 2007).

Restating the Research Questions

The following research questions, as stated previously, were designed in order to address the issues mentioned above concerning crop yield and rainfall in Jamaica and the parish of St. Elizabeth.

1) What is the effect of the MSD on the production of seasonal crops grown in Jamaica? How does the overall/seasonal crop production vary between 1965 and 2007?

2) Is there an optimal rainfall range for each crop within St. Elizabeth? Are there optimal locations within St. Elizabeth based on land-use and optimal rainfall ranges?

3) What are the impacts of the MSD on the vegetation within St. Elizabeth?

Chapter 3: Data and Methodology

Study Area

The Caribbean is comprised of hundreds of islands, varying in size, shape, topography and orientation. The island of Jamaica is located in the southern Caribbean, south of Cuba and west of the Dominican Republic and is illustrated as the island colored in red (Figure 4). Jamaica is comprised of varying degrees of elevation from the eastern mountains, the central valleys and plateaus and the coastal plains (Figure 5), and is broken up into 14 distinct parishes (Figure 6). It should be noted how the topography changes within each parish. This change plays a role in the types of crops that are grown. St. Elizabeth, also referred to as the "Bread Basket" of the country, has the largest expanse of flat terrain, which attributes in part to the parishes large crop yields every year.

Figure 4. Reference map for Jamaica.

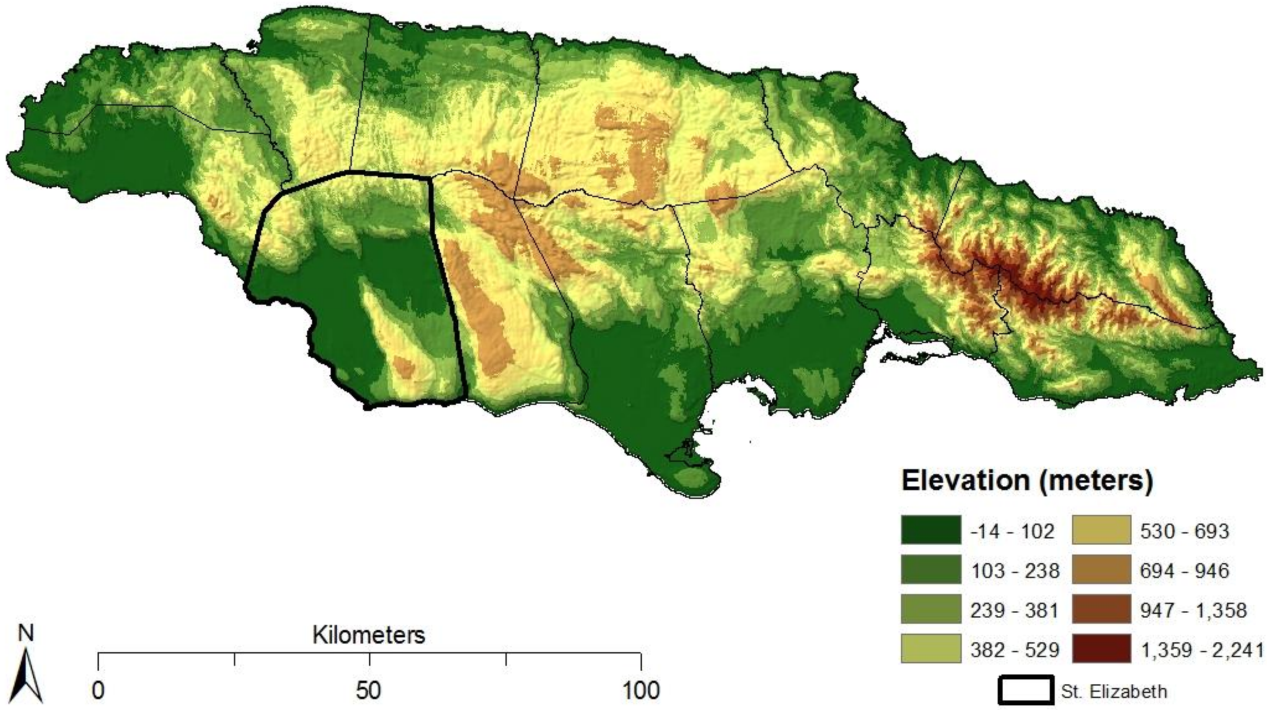


Figure 5. Topographical map of Jamaica with St. Elizabeth.

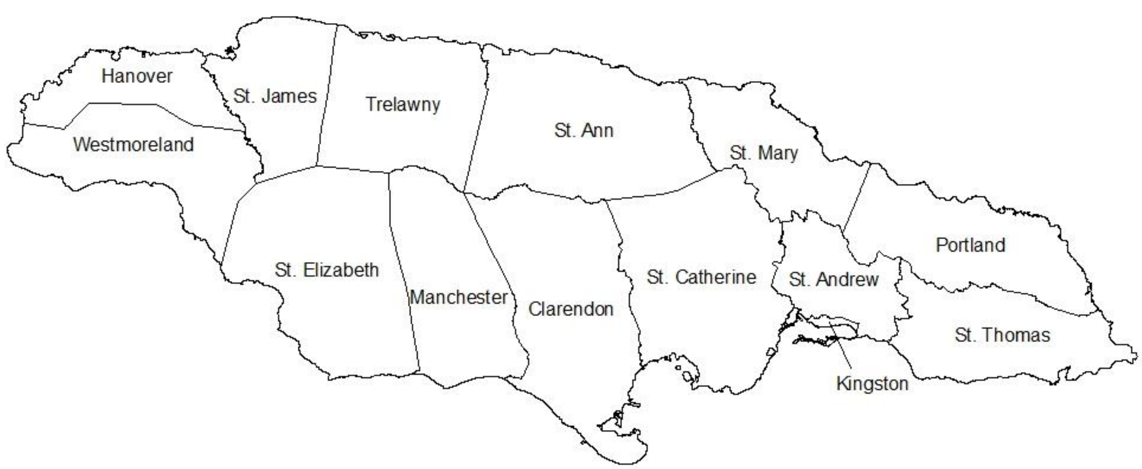


Figure 6. Image of the 14 parishes which make up the island of Jamaica.

Data

The data utilized in this study consisted of crop yield, rainfall, topography, and land-use datasets. A portion of the data was acquired from Donovan Campbell, a PhD student in Department of Geography at the University of West Indies at Mona, Jamaica. The data he contributed included: (1) Crop production yields for each of the 29 crops from 1965-2007; and (2) St. Elizabeth 30 year mean monthly rainfall.

Crop Data

The crop data that was received consisted of 29 different crops, with total crop production in tons and tons per hectare from 1965 to 2007. To justify using tons per hectare data as an important factor in crop growth for this study, correlations of tons to hectares were completed, to examine the relationship of tons of crops produced and hectares. Table 3 illustrates that there is a strong positive correlation for a majority of the crops. This finding indicates that the amount of hectares used when planting a crop is a factor in total crop growth.

To make the data easier to work with and to formulate conclusions about crop families, the crops were split into 8 different groups: vegetables, legumes, yams, other tubers, fruits, condiments, plantains and cereal (Table 4).

Table 3. Correlations between tons and hectares.

Crop Type		Crop Type	
Beetroot	0.81	Okra	0.71
Bitter Cassava	0.84	Onion	0.97
Cabbage	0.78	Ordinary Corn	0.96
Carrot	0.76	Other Lettuce	0.20
Cauliflower	0.99	Peanut	0.96
Coco	0.90	Pineapple	0.94
Cow Peas	0.99	Pumpkin	0.57
Cucumber	0.96	Red Peas	0.96
Dasheen	0.63	String Bean	0.94
Egg Plant	0.87	Sweet Cassava	0.50
Escallion	0.78	Tomato	0.61
Gungo Peas	0.97	Turnip	0.63
Horse	0.82	Watermelon	0.97
Lucea	0.88	Yams (Yellow)	0.97
Negro	0.61		

Table 4. Types of crops and their group name.

Vegetable	Legumes	Other Tubers	Yams	Fruit	Condiments	Plantains	Cereal
Beetroot	Cow Peas	Bitter Cassava	Lucea	Pineapple	Escallion	Horse	Corn
Cabbage	Gungo Peas	Coco	Negro	Watermelon	Onion		
Carrot	Peanut	Dasheen	Yellow Yams				
Cauliflower	Red Peas	Sweet Cassava					
Cucumber							
Egg Plant							
Okra							
Other Lettuce							
Pumpkin							
String Bean							
Tomato							
Turnip							

Rainfall Data

Island-wide Rainfall

The rainfall data consisted of two datasets. The first was acquired from the GPCP (Global Precipitation Climatology Project) Version 2.1, an international project that consists of monthly analysis of surface precipitation at 2.5^{o} latitude x 2.5^{o} longitude resolution available from 1979 (Huffman et al., 2009). The analysis incorporates precipitation estimates from low-orbit satellite microwave data, geo-synchronous-orbit satellite infrared data and surface rain gauge observations in order to calibrate or adjust the more frequent geosynchronous infrared observations. The GPCP data received specifically for this research consists of monthly precipitation averages from 2 grid boxes over western and eastern Jamaica for the period of 1979-2007.

Averages were taken between the two grid boxes over all months to produce an annual nation-wide mean. Since the GPCP data is comprised of satellite derived rainfall values, the accuracy of the estimated rainfall averages needed to be determined. In order to accomplish this, rainfall data from 1998 to 2007 was viewed and compared between the stations across the parish of St. Elizabeth and the GPCP rainfall data set. Examining this relationship, it was determined that the GPCP data was generally lower for a majority of the values.

In order to match the low GPCP rainfall values with the station data from St. Elizabeth, a regression was run to determine the coefficients required to calculate the corrected rainfall values for Jamaica. Using the computed coefficients the corrected rainfall values were calculated in an attempt to provide more accurate rainfall values for the island of Jamaica (Figure 7).

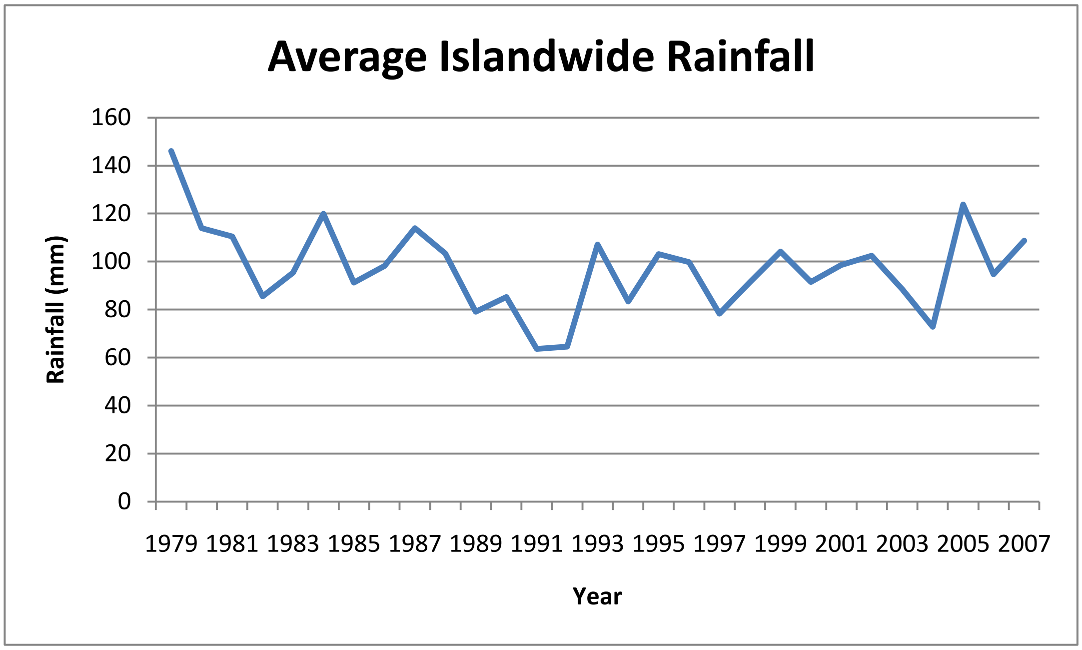


Figure 7. Average Jamaican rainfall 1979-2007.

The rainfall data was then split into two groups, early and late season, falling before and after the MSD based on Gamble (2010): April-June and August-November (Figure 8). It can be seen that there is not a significant difference between early and late season rainfall, but the late season tends toward a slightly higher amount of rainfall. Figure 9 illustrates the total monthly precipitation average over the entire time period from April to November. It should be noted that the bimodal rainfall pattern from the MSD can clearly be seen, with one rainfall peak in May and the second in October. The bimodality can further be seen in Figure 10, which illustrates the maximum and minimum average rainfall for the period. It can be seen that during the month of July, the peak month of the MSD, the maximum average rainfall drops significantly from June.

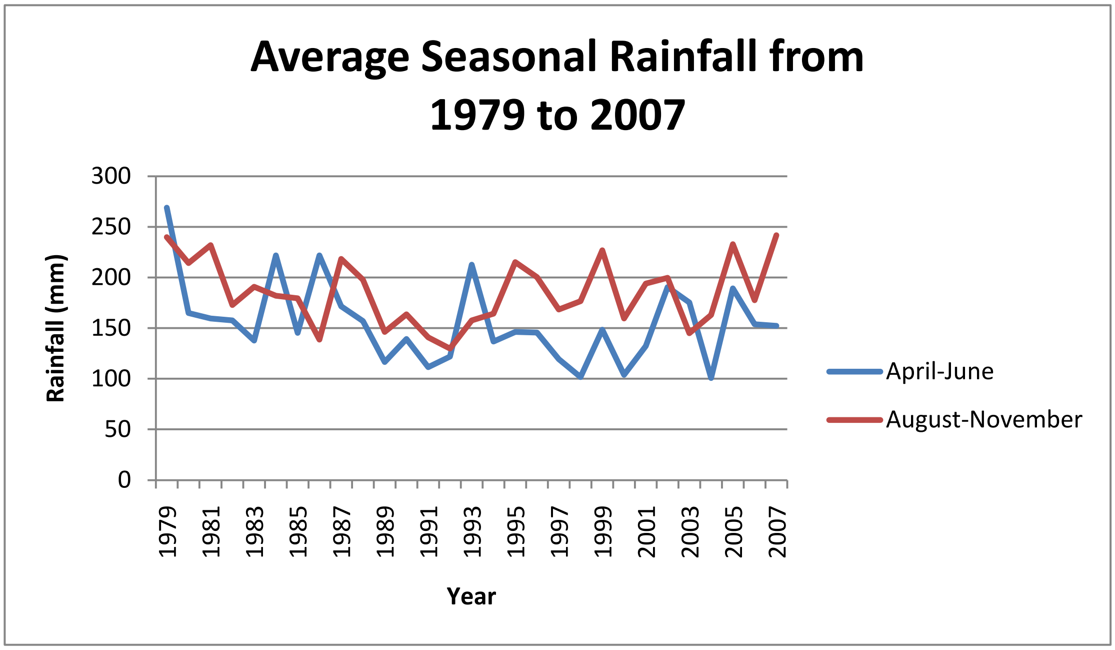


Figure 8. Average Jamaican rainfall for April-June and August-November from 1979-2007.

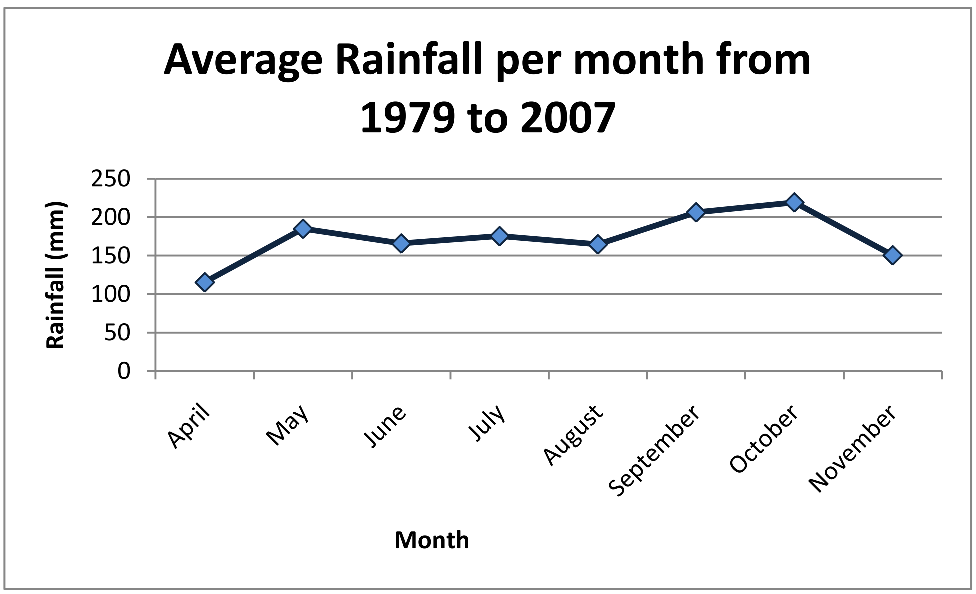


Figure 9. Average Jamaican rainfall per month from 1979 to 2007 (April-November).

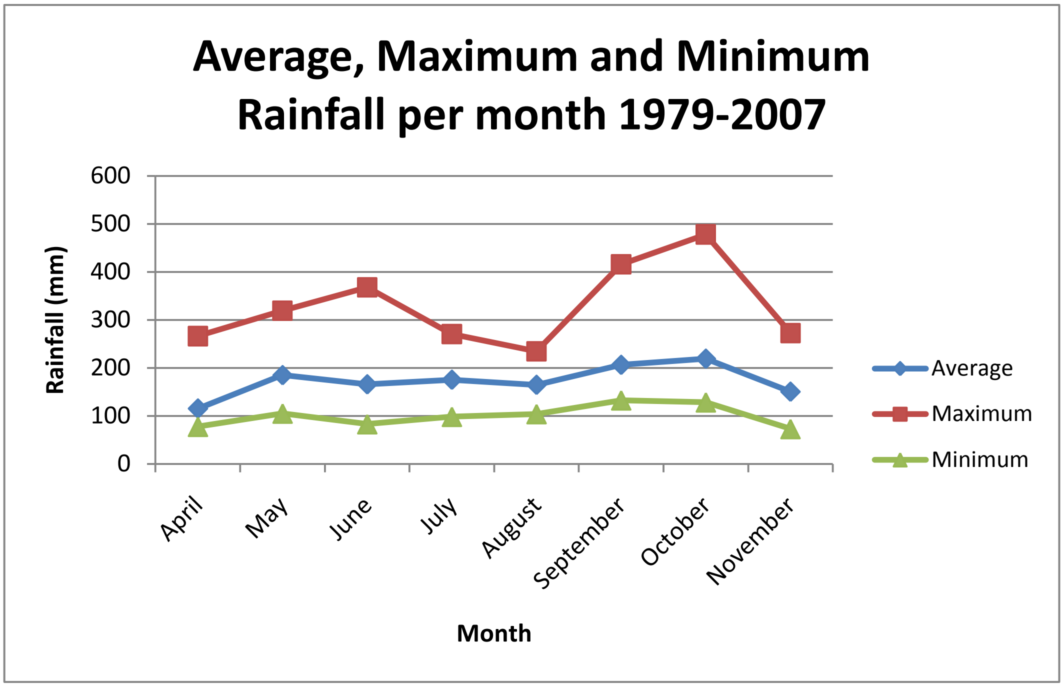


Figure 10. Average, maximum and minimum rainfall for Jamaica, 1979-2007.

St. Elizabeth

The second rainfall dataset consisted of 30 year mean monthly rainfall from 1951-1980 for the parish of St. Elizabeth for 55 stations. Unfortunately only 34 stations were used in this study due to a lack of latitude and longitude coordinates per station for mapping purposes. Figure 11 illustrates the spatial location of all 34 useable rain gauges within the parish, while Figure 12 illustrates the average amount of rainfall variation within St. Elizabeth per station. This variation is important because of the different rainfall requirements that different crops may have.

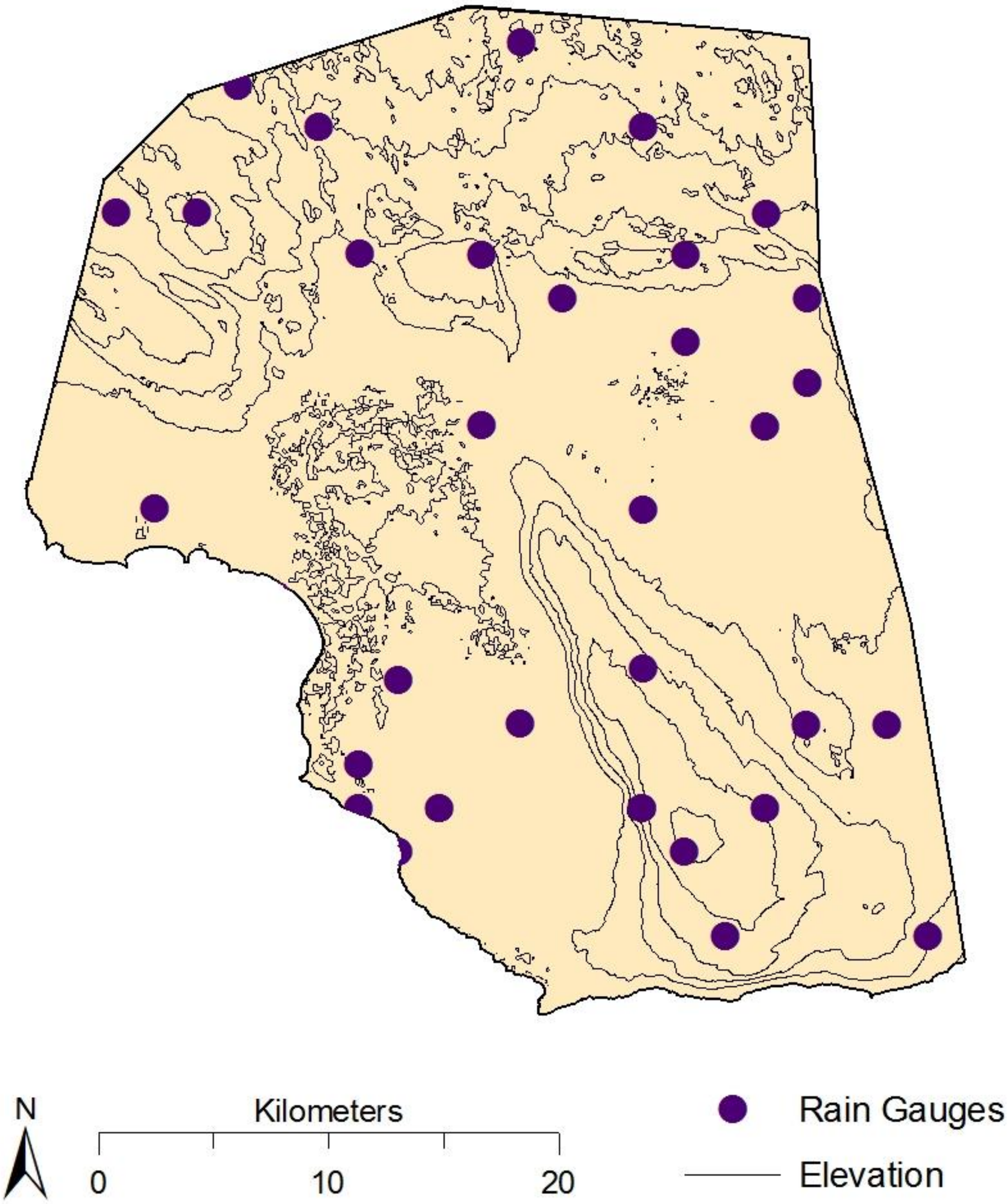


Figure 11. Locations of the 34 rain gauges within St. Elizabeth.

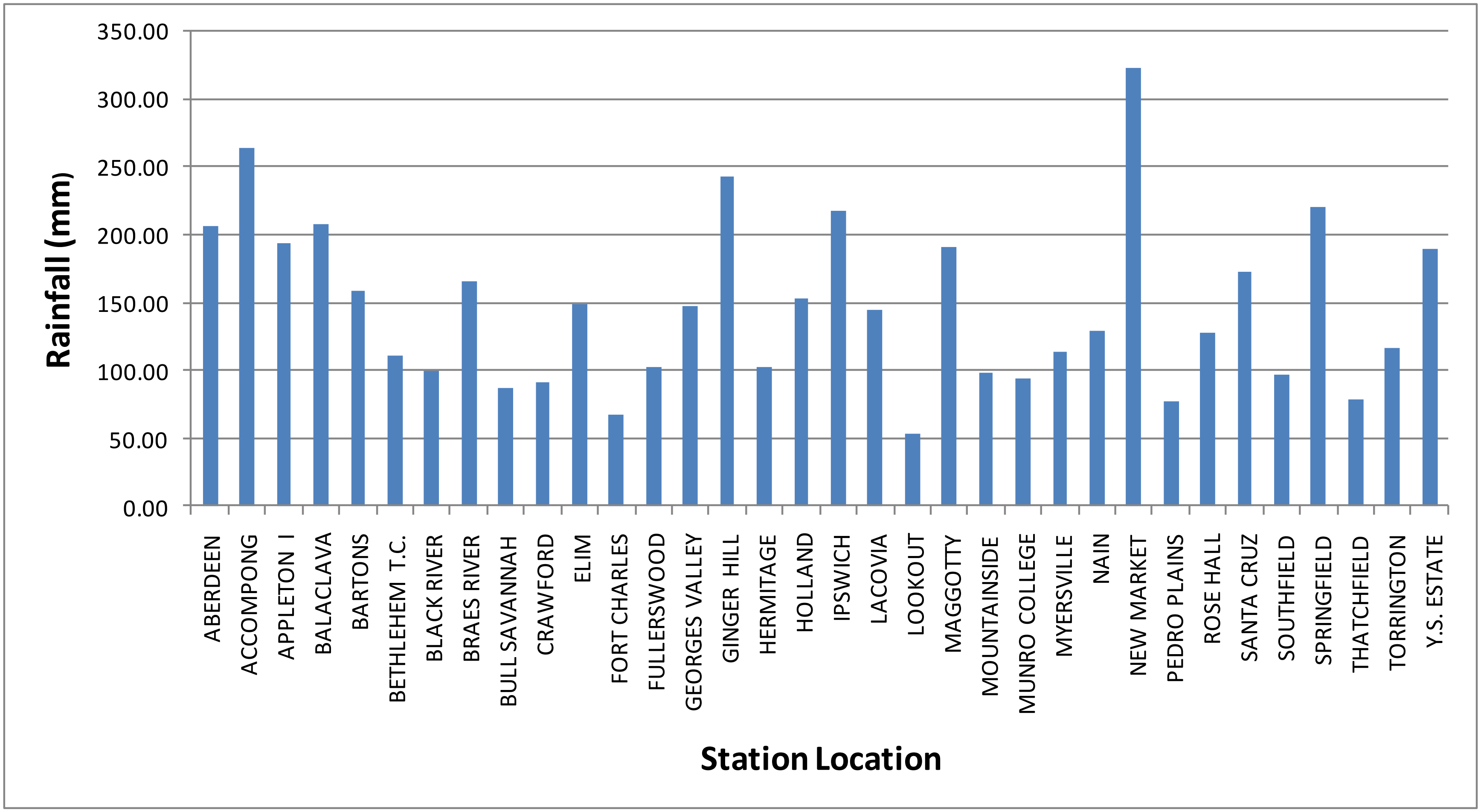


Figure 12. Average annual rainfall values from all 34 stations in St. Elizabeth.

Topographical Data

Topographical data for Jamaica was downloaded from The CIGAR Consortium for Spatial Information (CIGAR-CSI). The site provides Shuttle Radar Topographic Mission (SRTM) 90m Digital Elevation Models (DEMs) for the entire world. The vertical error of the DEMs is less than 16 m; see Figure 5.

Land-use Data

Land-use data for the island of Jamaica was downloaded from Jamaica's Ministry of Agriculture Forestry Department at a scale of 1:100000, from 1998. In order to understand the amount of farming that occurs on the island, a land use map was composed illustrating the four land use types where crops are being grown, these include (1) bamboo and fields, (2) fields, (3) secondary forest and (4) fields and plantations (Figure 13). It can be seen that a large portion of the island is for agriculture and that the majority of the farming takes place in the southern portion of Jamaica. A significant amount occurs in the parish of St. Elizabeth, also known as the breadbasket of the region, which is consistently ranked first or second in annual crop yield (Beckford et al, 2007).

Figure 14 illustrates how land is being used in the parish of St. Elizabeth, with topography overlaid. A majority of the parish is comprised of basic fields, with a scatter of secondary fields, plantations and a very small portion of bamboo and fields. It can be seen that a large portion of crop growth takes place in the lower elevations and in the southern portion of the parish.

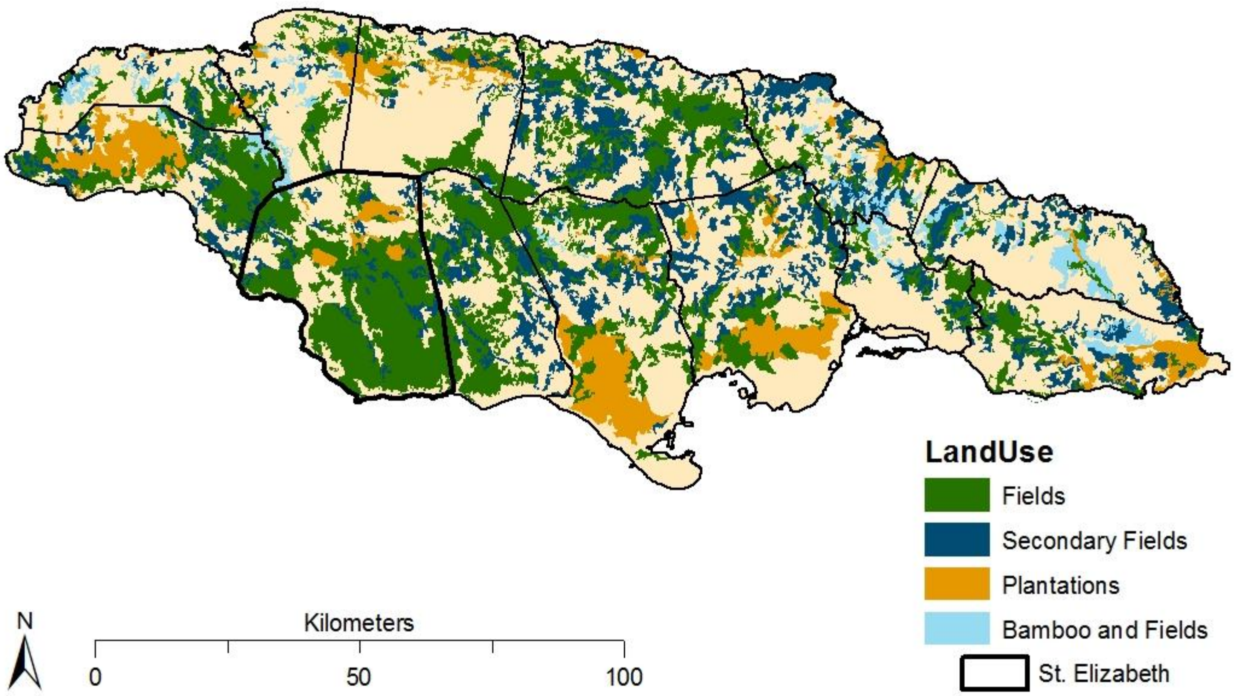


Figure 13. Land use map of Jamaica.

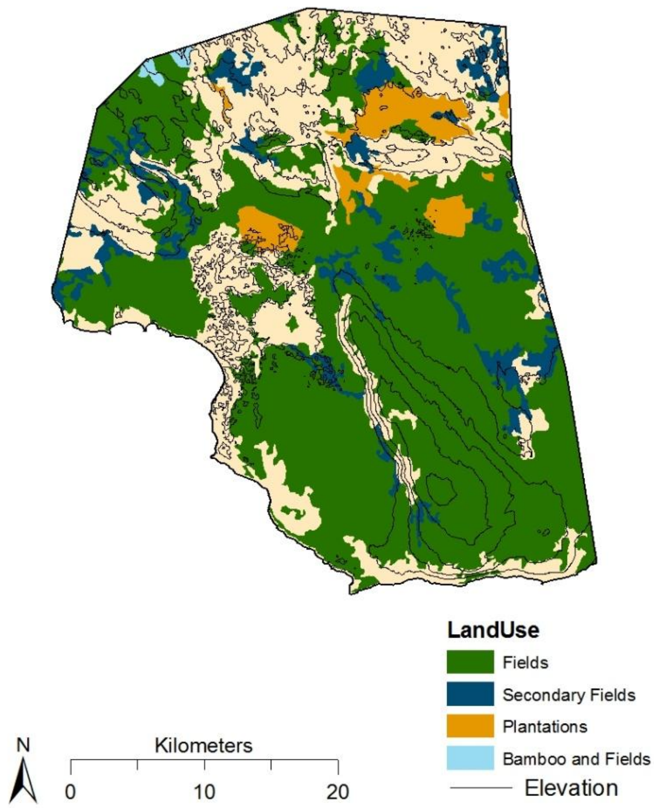


Figure 14. Land use map of St. Elizabeth with topography (150m).

Landsat Imagery

The Landsat imagery utilized in this study was acquired from the USGS Earth Explorer. Five months of images were chosen for the parish of St. Elizabeth surrounding the MSD with limited cloud cover for the best possible images and analysis. The months chosen include: May 11, June 28, July 14, August 31 and September 16 in 1987. The files were downloaded and imported into ERDAS IMAGINE 9.3 as image files. The 6 individual bands of each image had to be stacked together in order to allow for different combinations of RGB to be shown.

Since the parish is located between two path-rows, the number of images is doubled to 10 instead of 5, thus the images had to be mosaicked together in order to form a complete picture of the study area. The area of interest, St. Elizabeth, was then found in order to make the imagery smaller and easier to work with within ERDAS. The 5 resulting mosaicked and reduced images could then be clipped down to depict the parish of St. Elizabeth. Figure 15 illustrates the final visible Landsat imagery for May-September, depicting the features of the land. It can be seen that moving from May to August the amount of cloud cover increases slightly in the southern portion of the parish. The sharpness of the images also decreases, this is due to haze in the atmosphere, but should not affect the analysis.

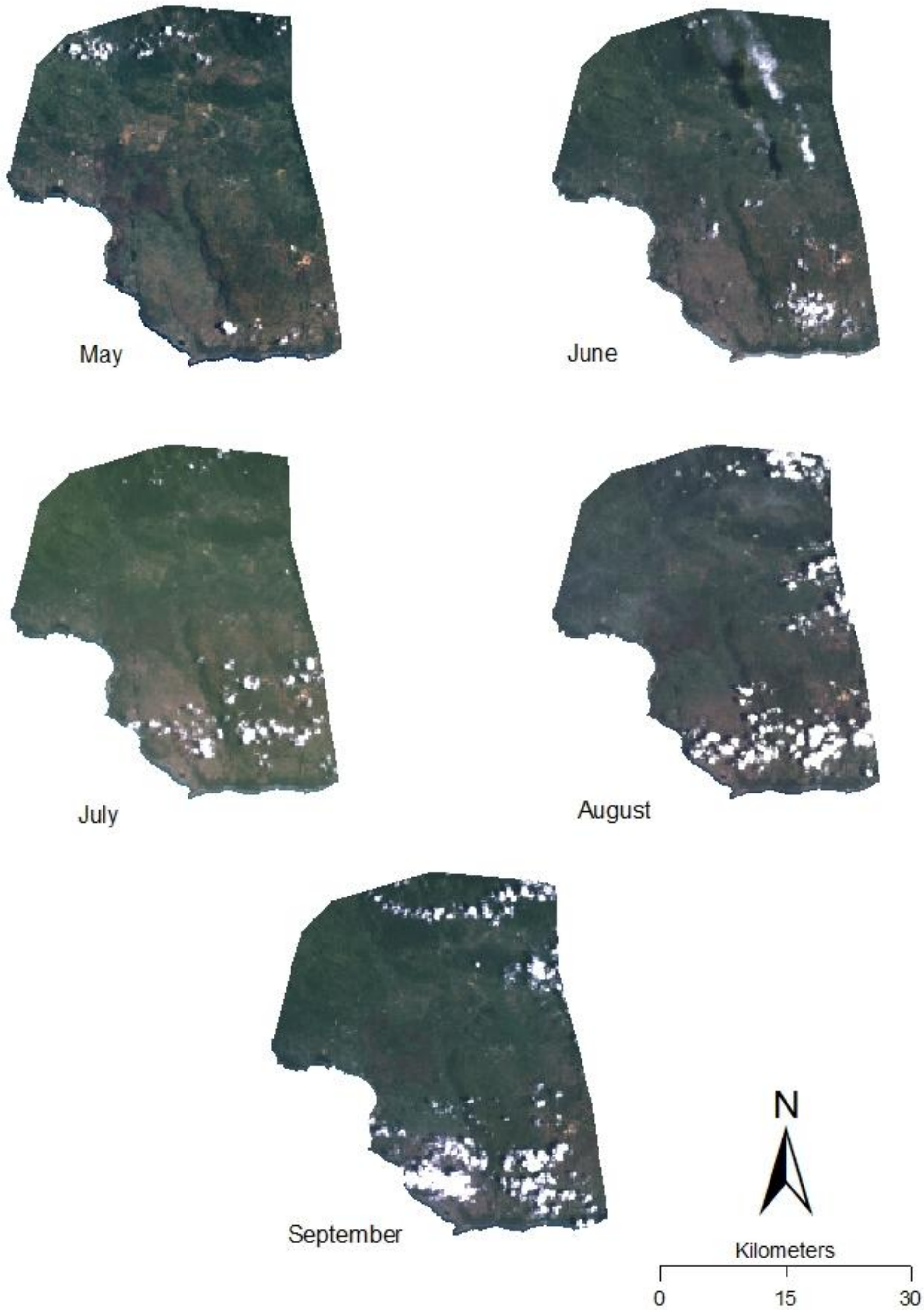


Figure 15. Visible Landsat imagery for the parish of St. Elizabeth (May-September 1987).

Methodology

The first portion of this research is to understand how rainfall affects crop growth during different time periods. In other words, how rainfall during the MSD months affects crop growth versus how rainfall during non MSD months affects crop growth. To accomplish this, correlations between crop growth and rainfall will be compared.

In order for the correlations to align, the same years had to be chosen for both crops and rainfall, thus the study is conducted from 1979 to 2007. Before any correlations could be run, the data had to be detrended. Detrending the data is important because historical yield data integrates a number of factors in addition to climate variability, including economic cycles and technological advances. Detrending separates the effects of inter annual climate variability from other factors that tend to change more slowly. Thus the seasonal and yearly changes can be seen more distinctly.

The second portion of the methodology will include examining rainfall within a specific parish in Jamaica in order to qualitatively evaluate the relationship of rainfall over the MSD period and to understand how elevation plays a role. The parish of St. Elizabeth has been analyzed previously with satellite data but not at the station level. To accomplish this, Geographic Information Systems (GIS) will be utilized; mapping 30 year monthly mean rainfall within St. Elizabeth, in order to visualize the rainfall over the entire parish throughout the year.

The method of Ordinary Kriging will then be applied to the rainfall points in order to create an interpolated map of rainfall over the entire parish. Ordinary Kriging is a spatial estimation method where the error variance is minimized. This error variance is called the kriging variance. It is based on the configuration of the data and on the variogram, hence is homoescedastic (Yamamoto, 2005). It is not dependent on the data used to make the estimate

(Lefohn et al., 1988). The monthly rainfall interpolations will then be quantitatively compared to the topography and elevation in order to see if a relationship or pattern arises between the two.

A principal component analysis (PCA) will be run in order to quantitatively evaluate the possible relationships between rainfall, elevation, slope and aspect. The input variables will include raster files of the monthly interpolated rainfall, elevation, slope and aspect. Running a PCA compresses the data by eliminating redundancy. For example, since slope and aspect are usually derived from elevation, most of the variance within the study area can be explained with elevation. The result of the PCA is a multiband raster with the same number of cells in the output that were in the original. The first principal component will explain the greatest variance, the second will show the second most variance not described by the first, and so forth (Kauth and Thomas, 1976). Although the PCA output provides matrices of the covariance and the correlations as well as eigenvalues and eigenvectors, the emphasis will be placed upon the correlations. The layers run in the PCA for this research will correspond to the following values: Layer 1-monthly rainfall interpolation raster, Layer 2-topography, Layer 3-Slope, and Layer 4-Aspect.

Additional analysis will be conducted to understand optimal rainfall ranges for each crop in order to maximize potential production. This will be accomplished by calculating the ranges per crop for annual, early and late season rainfall from 1979 to 2007 using the satellite derived GPCP rainfall and annual crop yield for Jamaica. The datasets were aligned and then ordered from most to least, based on the detrended crop yield. Thus crops with higher detrended crop values aligned with years of higher productivity, and their corresponding rainfall values.

The 10 most and least productive detrended crop growth years and their rainfall values can be extracted, forming the ranges of suitability per crop and per rainfall season; Table 5 illustrates an example of this for Beetroot, for all rain periods. This methodology extracts rainfall ranges that are either exclusively in the top performing category or bottom performing category.

Table 5. Example of minimums and maximums for the most and least productive years.

	Most Productive			Least Productive		
	Min	**Max**	**Range**	**Min**	**Max**	**Range**
Beetroot-Annual	106	162	55	122	198	75
Beetroot-Early	104	213	109	101	222	121
Beetroot-Late	130	232	102	139	233	94

Once the optimized ranges are determined per crop, a list of rules can be created in order to determine what rainfall amounts are suitable or unsuitable for crop growth. Table 6 shows the suitability rules calculated from the minimum and maximum values described previously in Table 5. This is important because agricultural efficiency can be determined through the understanding of where crop growth is either suitable or unsuitable.

Table 6. Example of suitability rules.

Crop Type-Rain Season	Suitability Rules (mm)
Beetroot-Annual	106 to 122 Suitable , > 162 Unsuitable
Beetroot-Early	< 104 Unsuitable, > 213 Unsuitable
Beetroot-Late	130 to 139 Suitable , > 232 Unsuitable

Using the rules of suitability per crop and per season, as well as the land-use map, GIS can be used to create a map visualizing where certain crops would best be planted for higher agricultural efficiency. It is important to understand that these rules, while calculated using island wide data, will be adjusted to make suitability maps within the parish of St. Elizabeth.

The final part of this study is to understand how the MSD impacts brightness, greenness and wetness of the land and vegetation. Analyzing change in vegetation over a time period can help determine vegetation vigor over the MSD period. In order to accomplish this, a Tasseled Cap transformation will be conducted. The Tasseled-Cap Transformation is a conversion of the original bands of an image into a new set of bands with defined interpretations that are useful for vegetation mapping. The transformation will be run and analyzed using ERDAS IMAGINE. The ERDAS system performs advanced remote sensing analysis and spatial modeling in order to create new information (ERDAS, 2011).

The original reason for developing the TC transformation was to capture the variability in spectral characteristics of various agriculture crops over time with indices related to brightness, greenness and wetness; "as crops emerged in the spring the relative differences in growth and phenology could be summarized (Franklin, 2001)."

The TC transformation attempts to reduce the amount of data layers needed for analysis. When a TC transformation is performed on six Landsat TM bands, six new layers are produced, with the first two bands containing the most information (95-98%) (Jensen, 1996, p182).

Crist and Cicone (1984) modified the TC to deal with six-band Landsat TM image; where the thermal infrared band numbered 6 is excluded. The six-dimensinal TM Landsat image is transformed into three new coordinate axes called brightness, greenness and wetness. The first tasseled-cap band corresponds to the overall brightness of the image; this index shows bare areas such as agricultural fields, beaches and parking lots as the lightest features. The second tasseled-cap band corresponds to "greenness" and is typically used as an index of photosynthetically-active vegetation; displaying healthy, green vegetation as the lightest feature. The third tasseled-cap band is often interpreted as an index of "wetness" (e.g., soil or surface moisture) or “yellowness” (e.g., amount of dead/dried vegetation) (Jensen 1996 p183, Jason Karl and Tso and Mather, 2009).

The TC transformation was originally defined by Kauth and Thomas (1976) based on a spectral analysis of the growth of wheat in fields. The transformation got its name from the way that a graph looked when the red band values of pixels were plotted against the near infra-red pixel values. The TC transformation coefficients were defined against this graph to maximize the separation of the different growth stages of wheat. A recreation of the original image is illustrated below; Figure 17 (Thayer Watkins).

The inputs for the TC transformation within ERDAS include the stacked Landsat imagery and the corresponding coefficients. A different set of coefficients need to be used depending on the imagery (Crist, 1985 and Jensen, 1996). For this study Landsat-5 TM imagery is being utilized; the coefficients for this are depicted in Table 7.

Table 7. Coefficients for Landsat 5 TM.

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7	Additive term
B	0.2909	0.2493	0.4806	0.5568	0.4438	0.1706	10.3695
G	-0.2728	-0.2174	-0.5508	0.7220	0.0733	-0.1648	-0.7310
W	0.1446	0.1761	0.3322	0.3396	-0.6210	0.4186	-3.3828
4th	0.8461	-0.0731	-0.4640	-0.0032	-0.0492	0.0119	0.7879
5th	0.0549	-0.0232	0.0339	-0.1937	0.4162	-0.7823	-2.4750
6th	0.1186	-0.8069	0.4094	0.0571	-0.0228	0.0220	-0.0336

Chapter 4: Results

Jamaica

A first look at the correlations via the crop groupings (Table 8) indicates that the crop type plays a role in how strongly positive or negative the crops are correlated. The coloration within the table illustrates that the darkest reds indicate strong negative values while the darkest greens indicate strong positive values. The legumes group has a trend of positively correlated crops across the rain seasons with one strongly negative crop, cow peas, and one with a relatively high positive value, gungo peas. Other tubers, on the other hand, are relatively neutral yet have one strong positively correlated crop, coco. The vegetable group is generally positive throughout all three rainfall periods with a few crops performing better; okra, tomato and turnip. It is interesting to note that the strongest and weakest correlated crops are within the vegetable category; tomato and cauliflower respectively. The yams group had a general neutral pattern, with the correlations close to zero.

That crop data set was also tested for significance using a Two-Tailed significance test in order to determine if a relationship exists with the rainfall data. Crops highlighted in Table 8 indicate that there is 90% confidence that the relationship didn’t happen by chance. There were two crops that indicated significance, these included cauliflower (late season rainfall) and tomato (annual rainfall); representing the lowest and highest correlations respectively.

It should be noted that there wasn’t a large portion of significant values overall; this could be attributed to a majority of the correlations being fairly neutral. This is likely due to the fact that crop growth is a determinant of more complex socio-economic and atmospheric factors than simply the amount of rainfall.

Table 9 depicts the breakdown between positive and negative crop correlations. Annual rainfall has the highest number of positive correlations while early rainfall has the least. The higher correlations with annual rainfall are probably because it is being compared to annual yields. The overall spread is not noticeably large.

Figures 16-19 illustrate the four highest and lowest crop correlations. Tomato and ordinary corn have the highest values; the correlations align with annual and early rainfall respectively. Cow peas and cauliflower have the lowest values; with early and late season rainfall corresponding with the crops.

Table 8. Correlations of 34 crops versus annual, early and late season rainfall with significant correlations highlighted, 1979-2007 (Color is representative of correlation strength: Strong Positive - Green, Strong Negative - Red).

		Annual	Early	Late
Cereal	Ordinary Corn	0.231	0.319	0.093
Condiments	Escallion	0.210	-0.061	0.229
	Onion	-0.077	-0.066	-0.219
Fruits	Pineapple	-0.001	-0.063	0.056
	Watermelon	-0.019	-0.043	-0.062
Legumes	Cow Peas	-0.240	-0.297	-0.048
	Gungo Peas	0.206	0.159	0.242
	Peanut	0.062	-0.036	0.227
	Red Peas	0.019	0.171	-0.089
Other Tubers	Bitter Cassava	0.101	0.006	0.083
	Coco	0.253	0.253	0.194
	Dasheen	0.069	-0.049	0.113
	Sweet Cassava	0.124	0.048	0.118
Plantains	Horse	0.061	0.150	-0.096
Vegetables	Beetroot	-0.035	-0.079	-0.136
	Cabbage	0.154	0.159	0.060
	Carrot	0.166	0.164	-0.063
	Cauliflower	-0.291	-0.222	-0.373
	Cucumber	0.056	0.065	-0.028
	Egg Plant	0.069	-0.049	0.113
	Other Lettuce	0.008	-0.149	0.148
	Okra	0.205	0.086	0.251
	Pumpkin	0.217	0.136	0.122
	String Bean	0.110	0.065	0.182
	Tomato	0.444	0.268	0.317
	Turnip	0.241	0.175	0.308
Yams	Lucea	0.095	-0.063	0.161
	Negro	0.082	0.018	0.058
	Yams (Yellow)	-0.050	0.051	-0.064

Table 9. Breakdown of positive and negative correlations.

	Annual	Early	Late
Positive	22	17	19
Negative	7	12	10

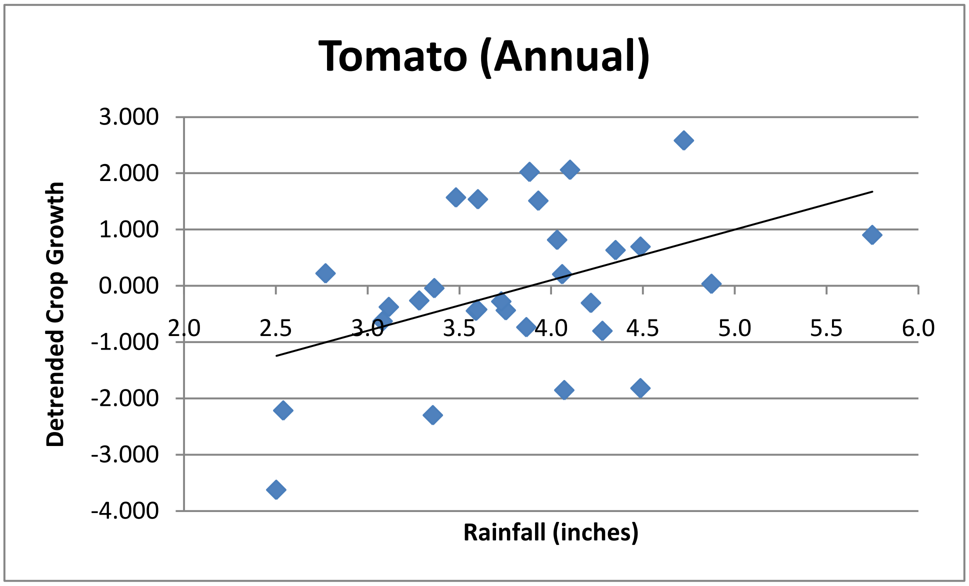


Figure 16. Scatterplot of tomato versus annual rainfall, 1979-2007.

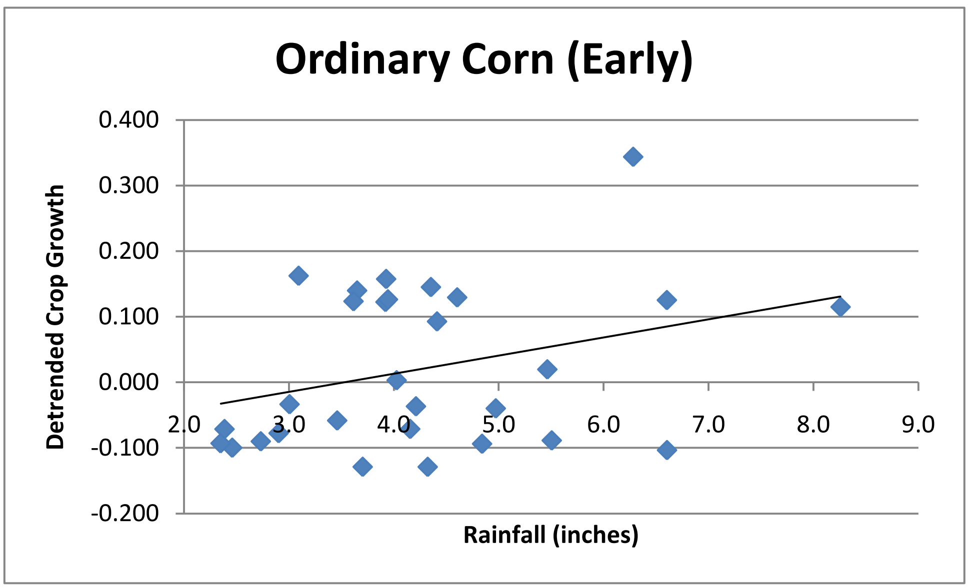


Figure 17. Scatterplot of ordinary corn versus early season rainfall, 1979-2007.

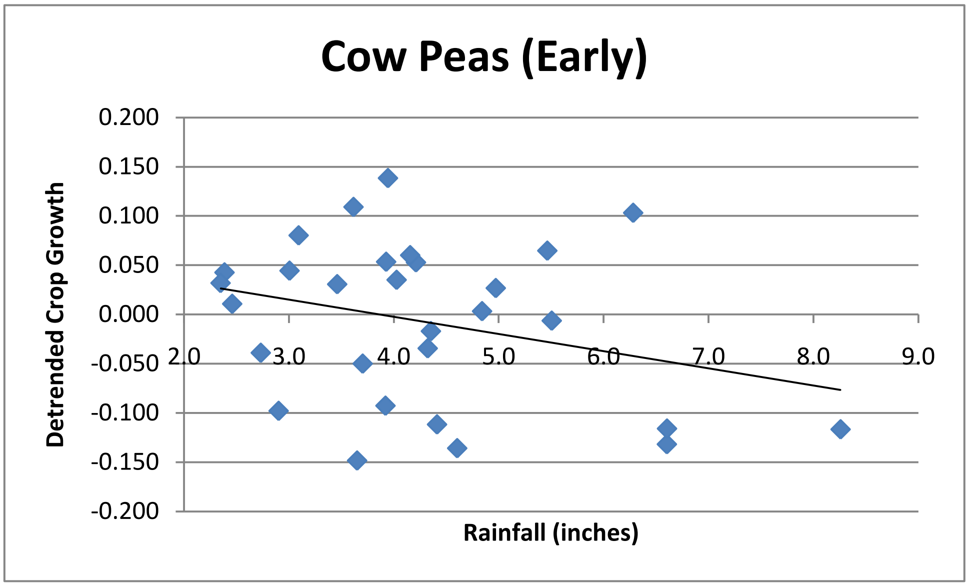


Figure 18. Scatterplot of cow peas versus early season rainfall, 1979-2007.

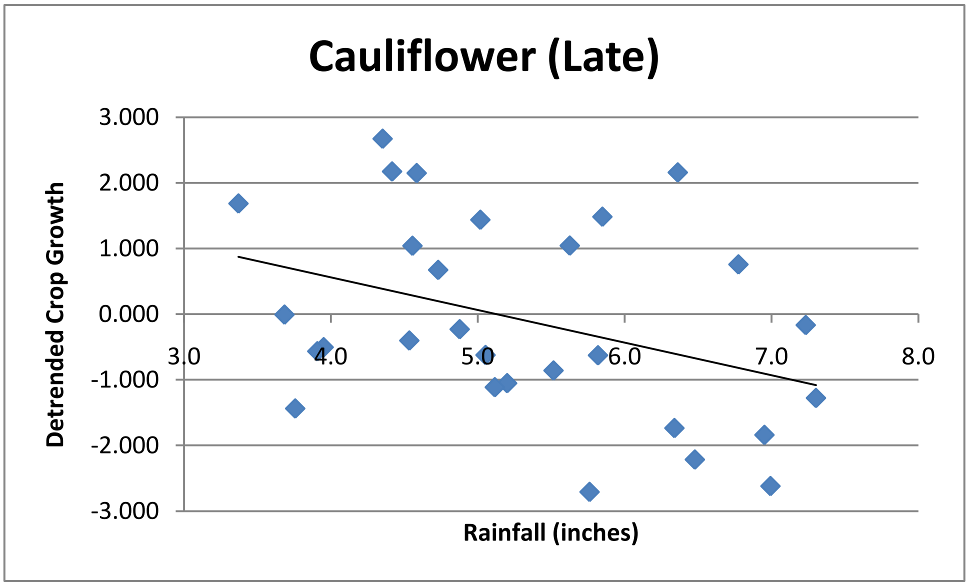


Figure 19. Scatterplot of cauliflower versus late season rainfall, 1979-2007.

Referring back to Figure 5, the topography of the island varies widely thus affecting the amount and spread of rainfall. The Mid-Summer Dry Spell (MSD) is an established atmospheric phenomenon that occurs throughout the Caribbean. The consequence of this occurrence is a bimodal annual rainfall with a peak in May/June and a second greater maximum in October (Taylor and Alfaro 2005, Magaña et al. 1999, and Small and Szoeke 2007).

What is unknown is how such a dip in rainfall affects crop growth. In order to answer this question, crop growth for Jamaica is tested for correlation with the average rainfall values per month from 1979 to 2007, for April-June (early season), July (MSD), and August-November (late season); Table 10 illustrates this.

The variation between the months is clearly evident through the coloration. The reds indicate strong negative values while the greens indicate strong positive values. Viewing the correlations this way results in some interesting patterns. While July is supposed to be the MSD period, it can be seen that it doesn't have the strongest negative correlations; it is actually composed of both negative and positive correlations. This could be attributed to tropical cyclones moving near or over the island, where flooding and wind can cause serious damage and be detrimental to crop growth. Of note, the months with the most negative correlations are September and October, and the month with the most positive correlations is November. The negative correlations occurring in September and October could be attributed to high wind and rains from hurricanes. While the rain could be welcomed, it is the high winds that can cripple crop growth.

The significances for the monthly correlations are illustrated in Table 10. In the month of April, the only significant crop was ordinary corn. The remaining significant crops occur during the month of November, these include: pineapple, gungo peas, lucea, bitter cassava, coco, dasheen, sweet cassava, and yams. Comparing the significances to the correlation table, it can be seen that November has the highest quantity of positive correlations. This large amount of strong positive correlations could be attributed to many of the crops requiring late season rainfall.

The maximum and minimum correlations from each month are shown in Table 11. There is an interesting array of correlations throughout the months. April can be seen with the lowest correlation and one of the highest correlations. This could be due to only a portion of the farmers actually plant their crops during this month, so there is higher variation in the crop yields. July, or the MSD month, has relatively neutral positive and negative correlations, generally hanging somewhere in the middle of the other months values. These values could be attributed to the understanding that it is by this time of the year that a majority, if not all farmers should have their crops in the ground and growing.

The monthly averages are also depicted (Table 11), illustrating that although April has the second highest positive correlation; it does not have the highest average. The highest average corresponds with November, followed by August, May, July, and then April.

Table 10. Correlations of crops versus monthly rainfall from 1979-2007 with significant correlations highlighted, (Color is representative of correlation strength: Strong Positive - Green, Strong Negative - Red).

		April	May	June	MSD Month	August	September	October	November
Cereal	Ordinary Corn	0.426	0.260	0.075	0.015	0.124	-0.048	0.025	0.183
Condiments	Escallion	-0.133	-0.042	0.014	0.307	0.278	0.074	0.057	0.198
	Onion	0.108	-0.022	-0.171	-0.191	-0.069	0.098	-0.349	0.002
Fruits	Pineapple	-0.128	0.097	-0.107	-0.114	0.056	-0.204	0.012	0.384
	Watermelon	0.056	-0.150	0.010	0.085	-0.024	-0.159	-0.106	0.289
Legumes	Cow Peas	-0.350	-0.013	-0.288	0.093	-0.045	-0.258	0.066	0.149
	Gungo Peas	0.153	0.077	0.120	-0.090	0.272	0.043	-0.034	0.466
	Peanut	-0.088	0.028	-0.030	0.141	0.338	-0.230	0.221	0.270
	Red Peas	0.256	0.192	-0.020	-0.188	0.156	-0.092	-0.225	0.223
Other Tubers	Bitter Cassava	0.036	0.050	-0.053	0.101	0.219	-0.059	-0.143	0.434
	Coco	0.160	0.320	0.082	0.131	0.280	0.088	-0.119	0.431
	Dasheen	-0.001	-0.014	-0.076	0.089	0.237	-0.048	-0.101	0.405
	Sweet Cassava	0.042	0.113	-0.035	0.065	0.201	0.006	-0.108	0.376
Plantains	Horse	0.162	0.302	-0.088	-0.104	-0.045	-0.020	-0.245	0.283
Vegetables	Beetroot	-0.220	0.265	-0.214	-0.106	0.052	-0.038	-0.212	0.067
	Cabbage	0.216	0.161	0.009	-0.052	0.199	0.070	-0.184	0.279
	Carrot	0.265	0.101	0.035	0.188	0.089	0.068	-0.175	0.012
	Cauliflower	-0.155	-0.002	-0.292	-0.203	-0.242	-0.180	-0.347	0.110
	Cucumber	0.225	0.035	-0.060	0.035	0.136	-0.011	-0.152	0.141
	Egg Plant	-0.025	0.168	0.349	-0.001	0.051	-0.165	0.019	-0.206
	Other Lettuce	-0.351	0.069	-0.092	0.211	0.217	-0.017	0.068	0.136
	Okra	-0.010	0.130	0.053	0.324	0.255	0.040	0.226	-0.004
	Pumpkin	0.220	0.091	0.024	0.076	0.255	0.049	-0.114	0.300
	String Bean	-0.072	0.171	0.022	0.221	0.244	-0.040	0.150	0.081
	Tomato	0.188	0.190	0.197	0.318	0.326	0.270	0.026	0.181
	Turnip	-0.034	0.220	0.152	0.268	0.306	0.044	0.202	0.153
Yams	Lucea	-0.080	0.023	-0.079	0.142	0.269	0.027	-0.118	0.433
	Negro	0.033	-0.024	0.030	0.174	0.225	0.073	-0.122	0.130
	Yams (Yellow)	-0.007	0.166	-0.041	-0.168	0.170	-0.081	-0.293	0.397

Table 11. Maximum and minimum correlations and averages per month, 1979-2007.

	April	May	June	MSD Month	August	September	October	November
Maximum	0.426	0.320	0.349	0.324	0.338	0.270	0.226	0.466
Minimum	-0.351	-0.150	-0.292	-0.203	-0.242	-0.258	-0.349	-0.206
Average	0.031	0.102	-0.016	0.061	0.156	-0.024	-0.072	0.217

St. Elizabeth Rainfall

Figures 20-31 illustrates the interpolated rainfall from January to December. Beginning with January and moving through April, one can see larger amounts of rainfall over the parish, while moving into the MSD period, June-July, rainfall amounts decrease significantly, especially over the southernmost portion of the parish. Continuing into the late season, rainfall amounts begin to increase again. It can be noted that throughout all months, the average rainfall in the southern portion of the parish is significantly lower than the northern portion.

It is also important to note how rainfall varies with topography and elevation on the island and with the parish itself. While St. Elizabeth has the largest expanse of level ground there are a couple areas with slightly higher elevation that can contribute to a change in rainfall. Referring back to Figures 20-31, the rainfall contours can be seen over the topography of the parish. These images are a good reference to how rainfall acts according to elevation. It should be noted that elevation does play a role in rainfall, but not during all months. January, February, September and October all show an increase in rainfall in the southern portion of the parish where topography is highest. The highest rainfall throughout all months occurs in the northern portion of the parish, where elevation is higher compared to the flatlands which surround it.

Difference maps were also calculated moving from May into September (Figures 32-35). The difference map of May and June (Figure 32) shows a decrease in rainfall in the northern portion of the parish with rather low positive rainfall values in the southern portion. Figure 33, the difference of rainfall between June and July, illustrates when the MSD period sets in, and is clearly visible. There is a large decrease in rainfall throughout the parish, although it should be noted that the northern portion has large positive values. During these two time periods, the MSD is seen moving south across the parish of St. Elizabeth from June to July. Figures 34 and 35 illustrate the differences of rainfall between July and August and August and September.

These difference maps are important because they depict that the MSD occurs in the northern mountains at least a month before the drought moves into the southern plains. Accordingly, the MSD recovers faster in the mountains, by one month, before it recovers in the plains. It is important to note that the MSD for the mountains begins in June and recovers in August while the MSD in the plains starts in July but doesn't recover until September. Such a difference could affect how and when farmers grow their crops. For instance, farmers in the mountains might need to plant one month prior to when farmers in the plains do.

Error maps were created for annual, early season and late season rainfall (Figures 36, 37 and 38) in order to depict the error of rainfall from the gauges throughout St. Elizabeth. All figures are similar in patterns, while the rainfall values (mm) vary between periods. Throughout the parish there is a relatively even distribution of stations, so the amount of error is relatively minimal, although there are some areas that have a higher amount of error.

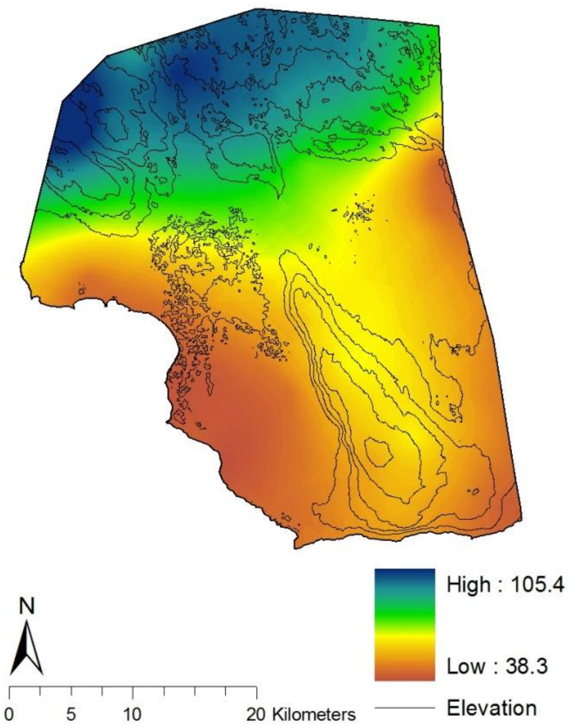


Figure 20. Interpolated January average rainfall 1979-1997 for St Elizabeth, Jamaica.

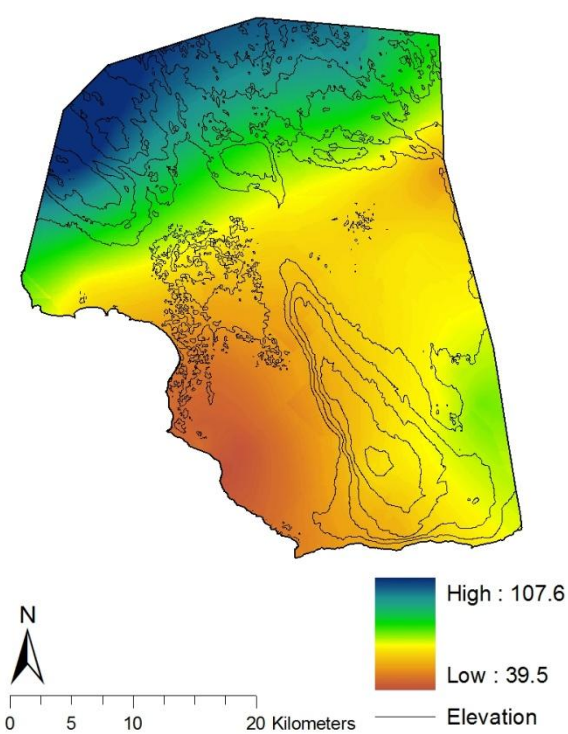


Figure 21. Interpolated February average rainfall 1979-1997 for St Elizabeth, Jamaica.

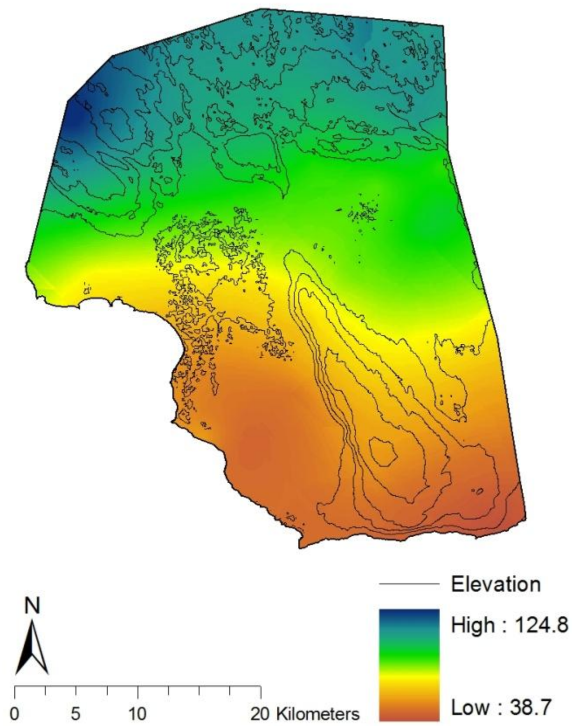


Figure 22. Interpolated March average rainfall 1979-1997 for St Elizabeth, Jamaica.

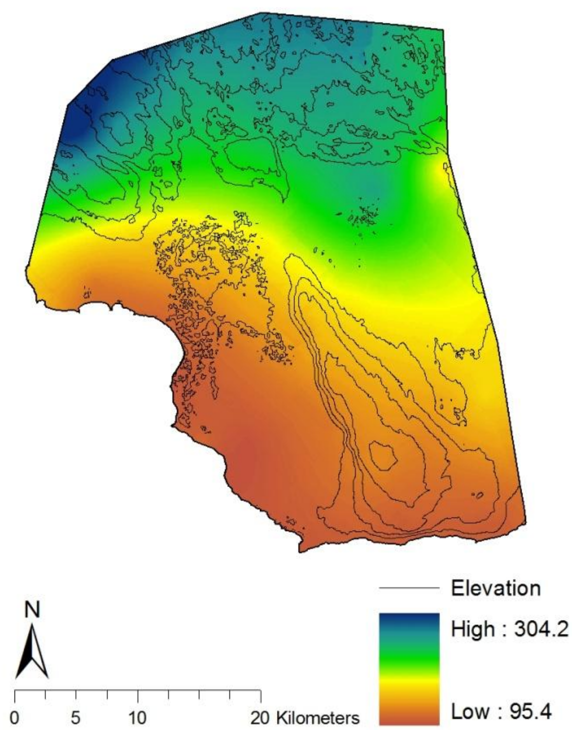


Figure 23. Interpolated April average rainfall 1979-1997 for St Elizabeth, Jamaica.

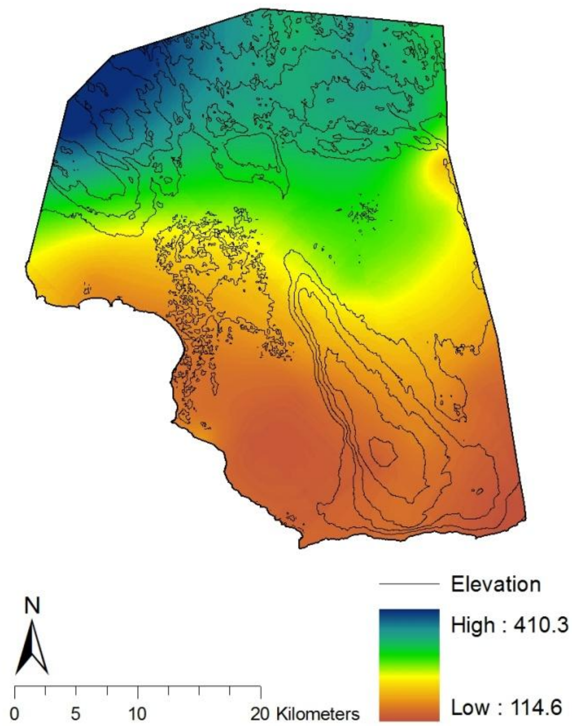


Figure 24. Interpolated May average rainfall 1979-1997 for St Elizabeth, Jamaica.

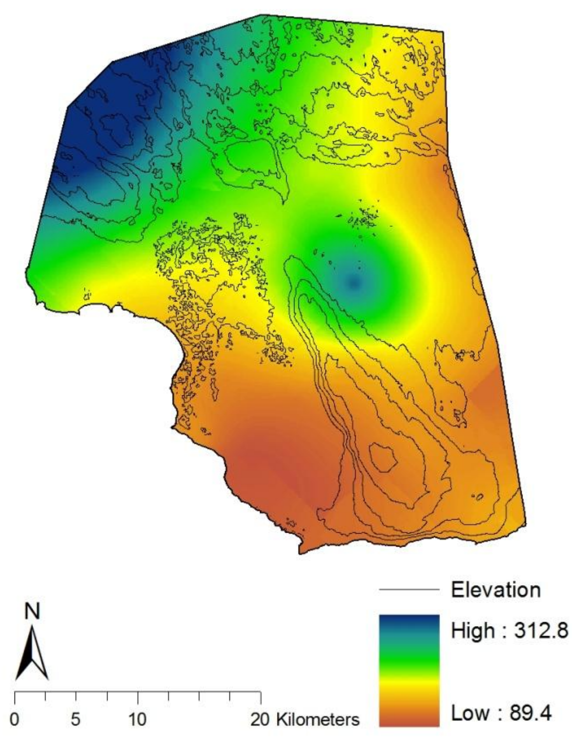


Figure 25. Interpolated June average rainfall 1979-1997 for St Elizabeth, Jamaica.

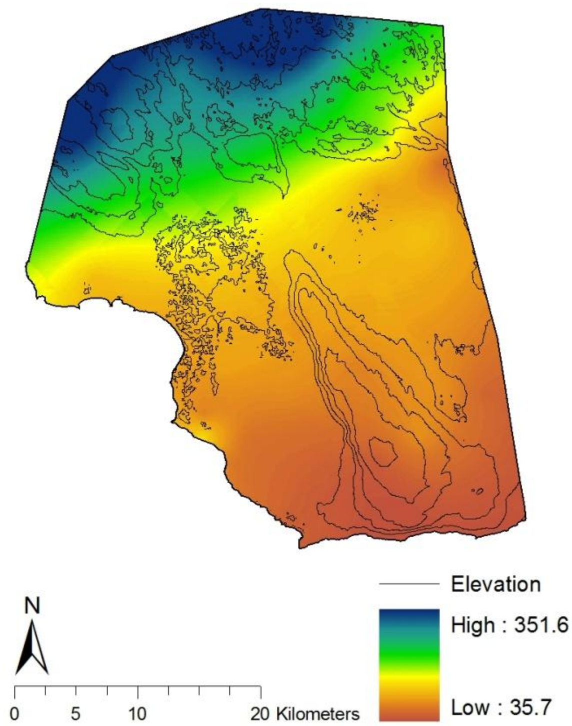


Figure 26. Interpolated July average rainfall 1979-1997 for St Elizabeth, Jamaica.

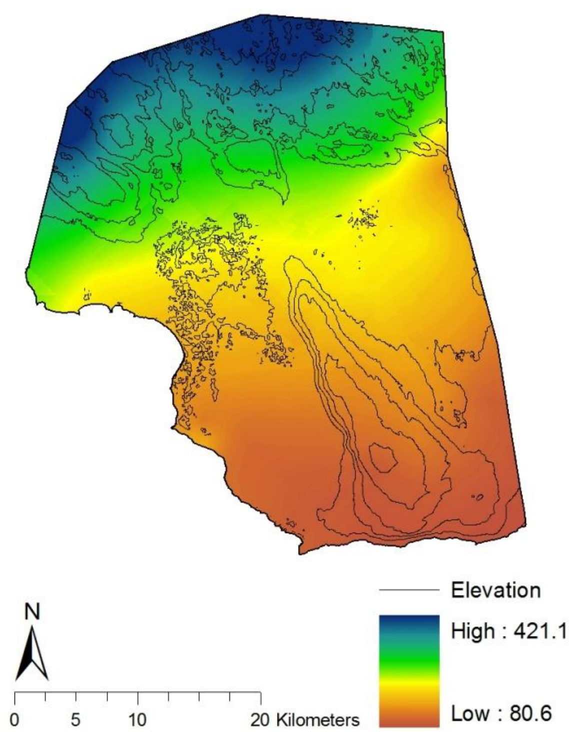


Figure 27. Interpolated August average rainfall 1979-1997 for St Elizabeth, Jamaica.

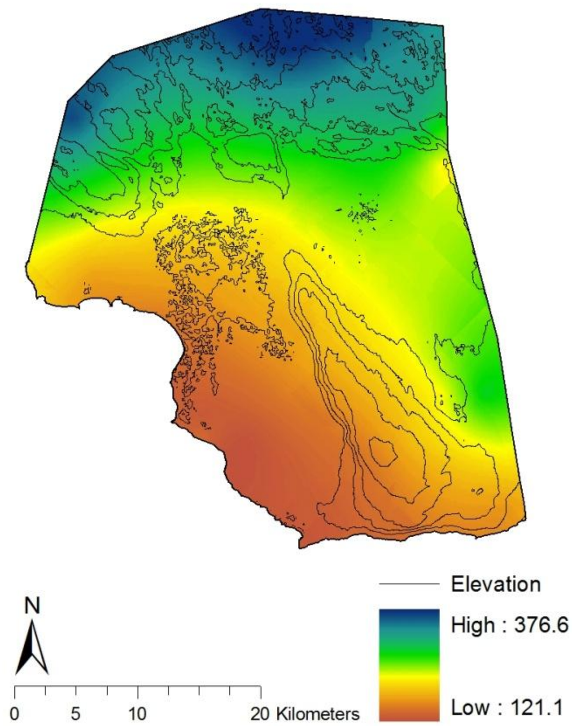


Figure 28. Interpolated September average rainfall 1979-1997 for St Elizabeth, Jamaica.

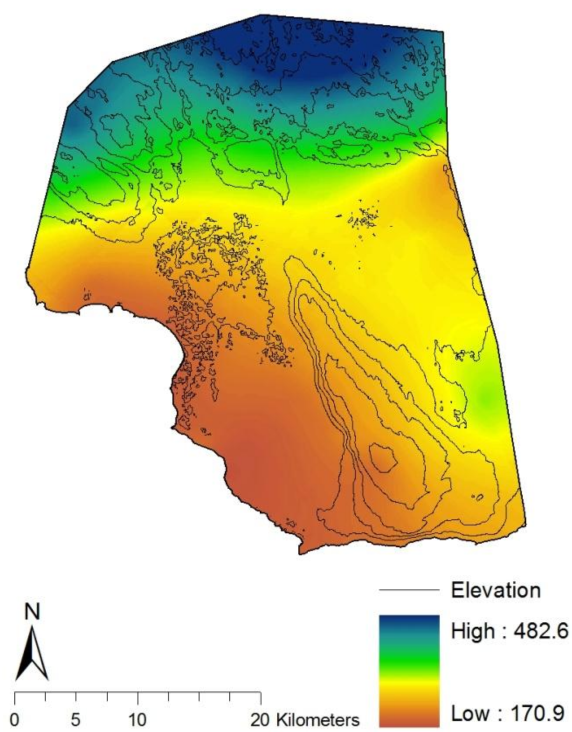


Figure 29. Interpolated October average rainfall 1979-1997 for St Elizabeth, Jamaica.

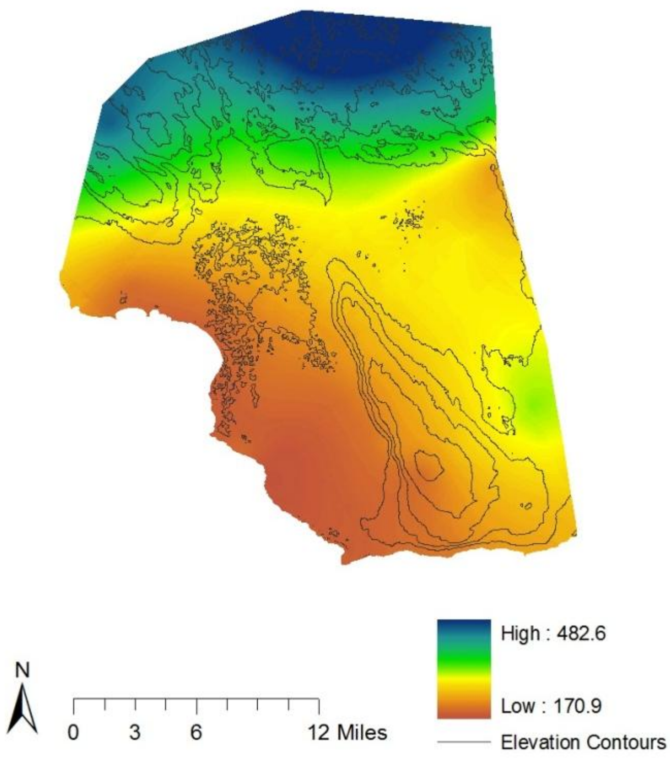


Figure 30. Interpolated November average rainfall 1979-1997 for St Elizabeth, Jamaica.

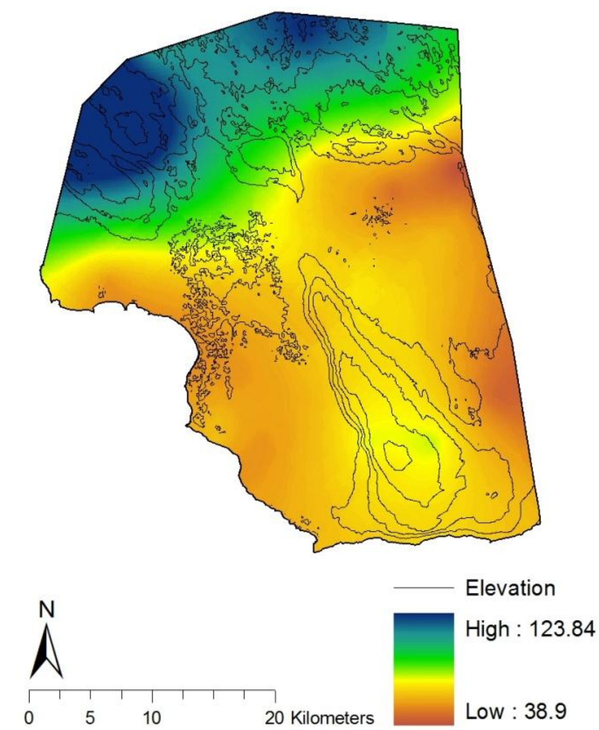


Figure 31. Interpolated December average rainfall 1979-1997 for St Elizabeth, Jamaica.

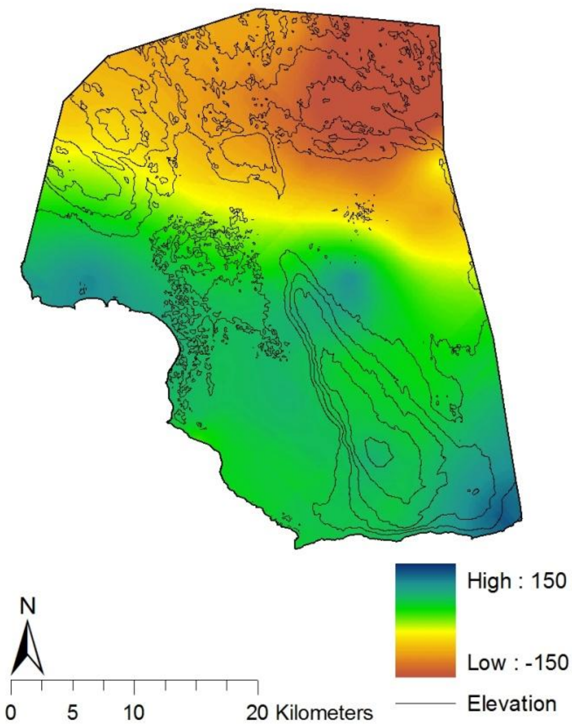


Figure 32. Interpolated rainfall difference between May and June 1979-1997 for St Elizabeth, Jamaica.

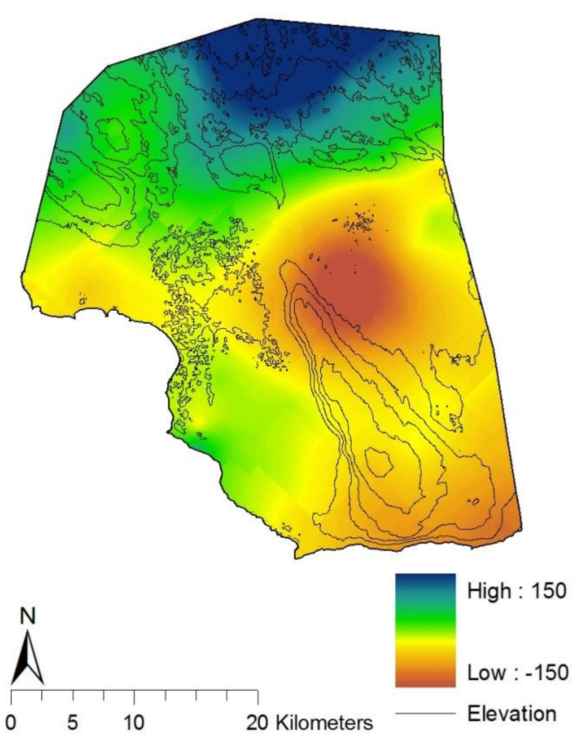


Figure 33. Interpolated rainfall difference between June and July 1979-1997 for St Elizabeth, Jamaica.

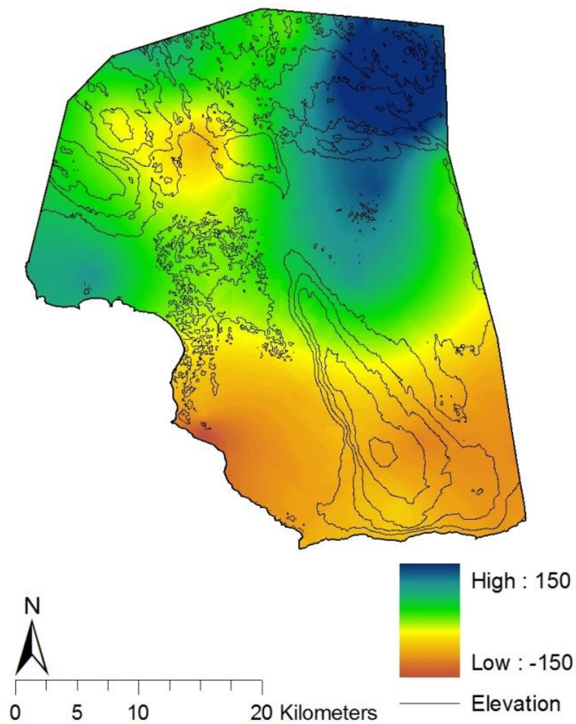


Figure 34. Interpolated rainfall difference between July and August 1979-1997 for St Elizabeth, Jamaica.

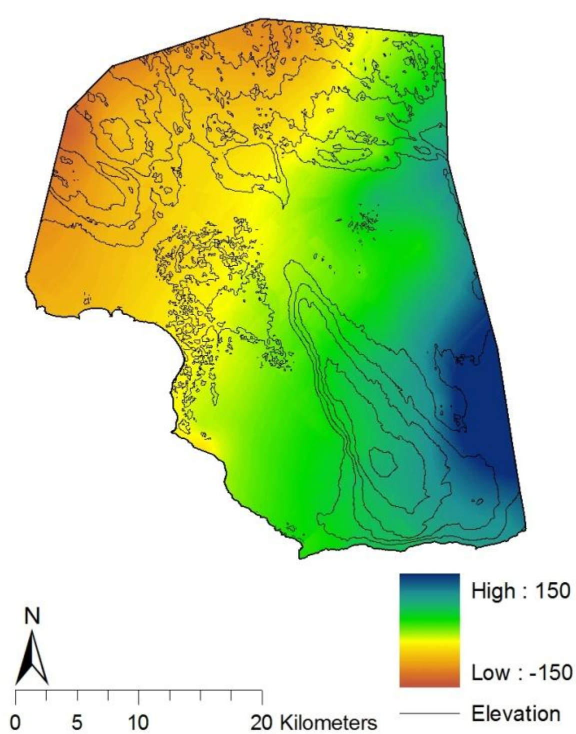


Figure 35. Interpolated rainfall difference between August and September 1979-1997 for St Elizabeth, Jamaica.

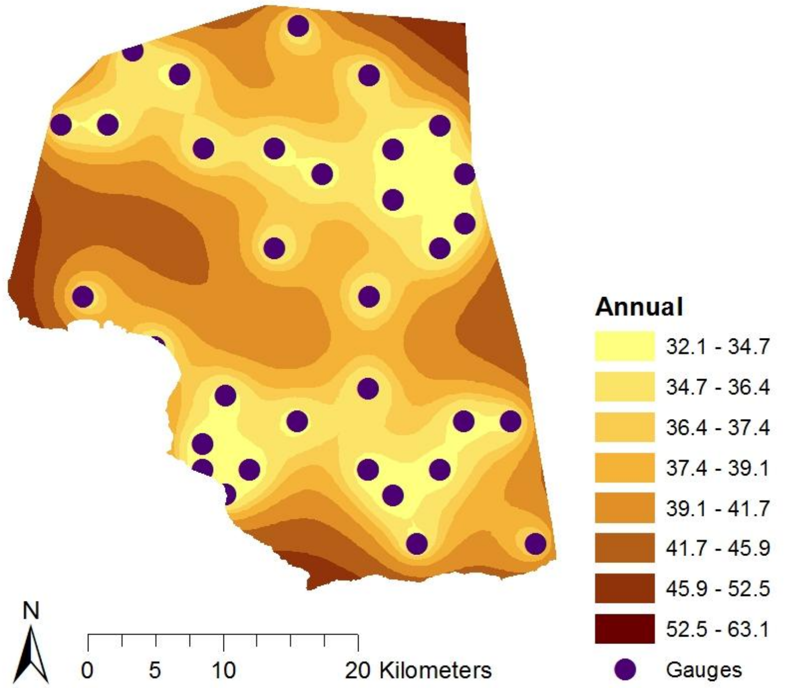


Figure 36. Error maps for the interpolated annual rainfall from 1979-1997 for St. Elizabeth, Jamaica.

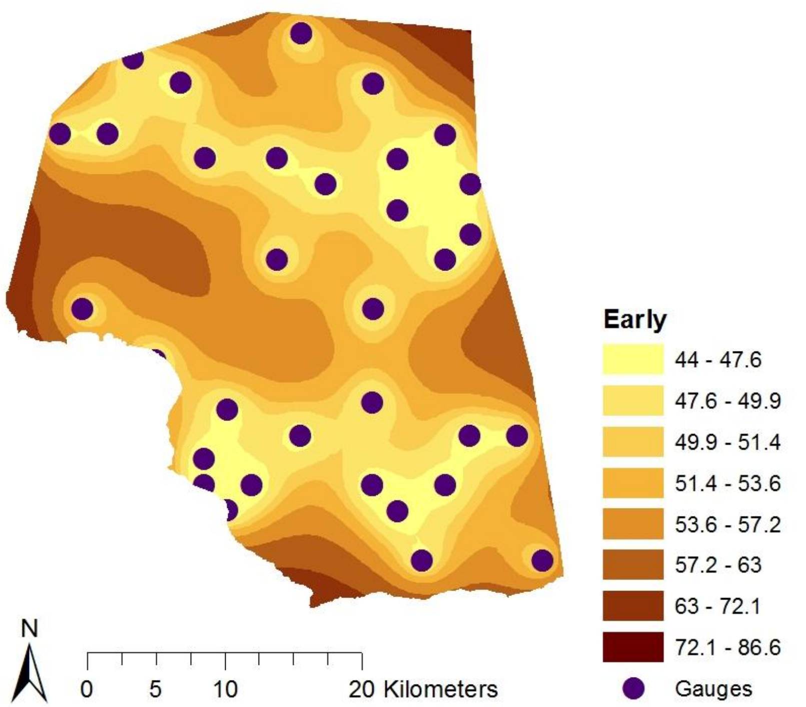


Figure 37. Error maps for the interpolated early season rainfall from 1979-1997 for St. Elizabeth, Jamaica.

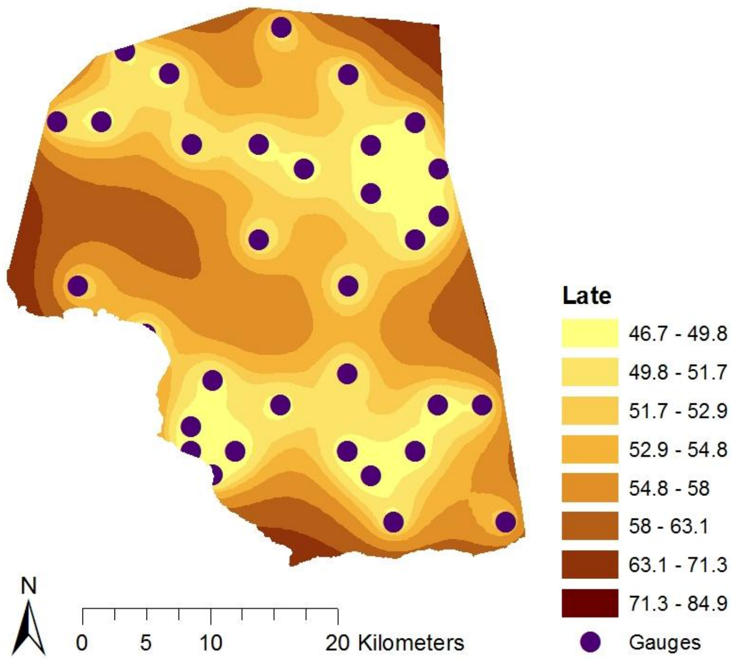


Figure 38. Error maps for the interpolated late season rainfall from 1979-1997 for St. Elizabeth, Jamaica.

Principal Component Analysis

A PCA was run for each month's interpolated rainfall as well as the difference maps in order to determine the quantitative relationship between rainfall, topography, slope and aspect; the results are indicated in Table 12. The only correlations that are important are those that deal with rainfall and elevation, the remaining variable of aspect is not relevant because it is not related to topography. The correlations between rainfall and topography are positive and indicate a change moving through the months. The correlations remain around 0.2 - 0.35 between January and May, and then drop to 0.1 in June, and rise back to 0.2 - 0.33 from July to December. It should be noted that the later months (September-December) have higher correlations compared to the rest of the months in the year.

Table 12 also illustrates the PCA for the difference maps produced previously (Figures 34-37). Here the correlations between the rainfall differences and topography show that between May and June, there is a negative correlation, while June to July indicates a positive correlation.

The PCA of the difference maps demonstrate that the MSD begins in June at high elevations and July at the low elevations. Between May and June, the MSD begins in the northern mountainous regions of the parish. This leads to lower rainfall values for regions with higher elevations, while the southern locales with lower elevations remain unaffected. This leads to the negative correlation (-0.245) between rainfall and elevation from May to June. As the MSD moves south, rainfall increases some in the higher elevations to the north and decreases in the lower elevations to the south. This is evidenced by the positive correlation (0.291) found between elevation and rainfall from June to July. The MSD begins its exit from the parish in July through September, as rainfall patterns slowly return to normal.

Table 12. PCA correlations for monthly interpolated rainfall, 1979-2007.

Month	Elevation	Slope	Aspect
January	0.250	0.211	-0.037
February	0.035	0.224	-0.017
March	0.260	0.234	0.021
April	0.257	0.214	0.014
May	0.214	.0210	-0.003
June	0.120	0.101	-0.047
July	0.235	0.196	-0.015
August	0.206	0.191	-0.006
September	0.333	0.247	0.015
October	0.339	0.256	0.001
November	0.311	0.224	0.005
December	0.328	0.220	-0.043
May-June	-0.245	-0.257	-0.048
June-July	0.291	0.241	0.033
July-August	-0.004	0.090	0.032
August-September	0.083	-0.011	0.032

Optimal Rainfall Ranges

The optimal rainfall ranges were comprised of maximum and minimum values for the 10 most and least productive years, as well as the ranges for all three rain periods; annual, early (April-June) and late season (August-November). It can be noted that the ranges are generally smaller for the most productive years compared to the least productive years throughout all rain periods (See Appendix A).

Suitability rules were calculated for each crop in order to determine which rainfall ranges were suitable or unsuitable for crop growth (See Appendix B). The rules were determined for annual, early and late season rainfall. It was found that the late season suitability rules have higher rainfall values compared to the annual and early season rules. It is interesting to note that there are some crops and rainfall periods that have rules where there are only suitable or unsuitable areas. This means that there are more areas within the parish that fit within those categories. It is important to note that although the suitable and unsuitable areas were defined, the remaining areas are still possible growth areas, but will not have the highest crop growth rates possible.

Agricultural Efficiency

Utilizing GIS, the suitability rules and the land use map, suitable crop growth areas can be determined for annual, early and late season rainfall. In order to accomplish this, new rainfall maps were created for the average annual, early and late season rainfall values. The areas where farming has been designated using the land use map can be extracted, thus showing the rainfall that occurs over those areas for the annual, early and late season rainfall (Figures 39, 40 and 41). Maps were then created comprised of suitable and unsuitable areas according to rain rates for significant and important crops within the region. There is a general trend of seasonal rainfall is along the same lines as that of the monthly rainfall; the highest values are located in the north-northeast and the drier area being the south-southwest. Table 13 indicates the overall rainfall ranges per season. The variability between the seasons can be seen, with the largest difference occurring in the late season.

Table 13. Overall rainfall ranges per season.

	Annual	Early	Late
Minimum	84	123	96
Maximum	282	367	368

In order to understand how the MSD affects crop growth within the parish of St. Elizabeth, one or two crops from each crop grouping were chosen (Table 14). The crops were chosen because they were significant during an individual rain period or were considered a significant cash crop for Jamaica.

Suitability maps (Figures 42-51) were then created for the 10 chosen crops in order to compare and contrast the difference between the rainfall seasons and the types of crops. Most crops illustrate suitability during annual rainfall, although there were several crops that depict suitability where the rainfall season correlations were significant. Maps for all crops during annual, early and late season rainfall can be seen in Appendices C, D and E.

Table 14. Crop groupings and crops chosen for a closer look.

Crop Group	Crop Type
Cereal	Ordinary Corn
Condiments	Onion
Fruits	Watermelon
Legumes	Cow Peas
Other Tubers	Bitter Cassava Sweet Cassava
Plantains	Horse
Vegetables	Cauliflower Tomato
Yams	Yams (Yellow)

<u>Cereal</u>

From the cereal crop grouping, ordinary corn showed positive correlations across all three rainfall periods. The two strongest were annual and early season rainfall. Figures 42a and b illustrate the suitability for both rainfall periods. It can be noted that annual rainfall indicates a strip of suitable crop growth in the south and a region of unsuitable growth in the north. Early season rainfall is dominated by unsuitability, with two separate regions in the north and south.

Condiments

Annual and late season rainfall for onion is illustrated in Figures 43a and b respectively. Annual rainfall shows two large areas of unsuitable crop growth in the north and the south. Late season rainfall, which corresponds with a large negative correlation, also shows a large region of unsuitability in the northern region of the parish and a strip of suitable crop growth along the southern coastline.

Fruits

Under the fruits crop group, watermelon showed relatively neutral negative correlations from all three rain periods. Crop suitability for annual rainfall indicates two areas of unsuitable crop growth in the north and the south (Figure 44).

Legumes

Between annual and early season rainfall, there is a distinct difference between suitable and unsuitable regions during annual and early rainfall for cow peas. Annual rainfall (Figure 45a) shows unsuitable crop growth in the south with a thin line of suitable growth in the north. Early season rainfall (Figure 45b) illustrates the opposite with unsuitability in the north and suitable crop growth in the southwest.

Other Tubers

Annual rainfall for bitter and sweet cassava can be seen in Figures 46 and 47 respectively. It is interesting to the note the difference between the two crops although they come from the same crop grouping. Bitter cassava illustrates two large regions of unsuitable crop growth while sweet cassava shows two smaller areas of suitable crop growth; following along the same paths.

Plantains

The horse plantain indicates two areas of suitable crop growth for annual rainfall: one within the north and one within the south (Figure 48). This is interesting to note because of a majority of the crops have both suitable and unsuitable locations throughout all three rainfall seasons. These regions are also the largest compared to all other crops that have two areas of suitability indicated.

Vegetables

Within the vegetable crop grouping, two crops were chosen, cauliflower and tomato. Figures 49a and b illustrate where crop growth is suitable and unsuitable for cauliflower during annual and late season rainfall. This crop and rainfall period had the highest negative correlation of the crops. It can be seen that there is a large area in the north that is unsuitable with a band of suitable crop growth conditions in the south running from west to east.

The tomato crop (Figure 50) follows the trend like many of the other crops, but with a large area of suitable crop growth in the south, and a strip of unsuitable crop growth in the north during annual season rainfall. This rainfall season can be compared to early and late, which have either only suitable or unsuitable regions, respectively, for crop growth. Tomato also had the highest positive correlation during annual rainfall.

Yams

Figure 51 shows the suitability of yams during annual season rainfall. Yams show a larger portion in the north as unsuitable for crop growth with a small strip in the center sloping to the south, suitable for crop growth.

Throughout a majority of the suitability illustrations, the areas of unsuitability and suitability seem to follow a general pattern, with either a large unsuitable portion in the north and the south or smaller strips of suitable crop growth. The suitability patterns also follow an east-west zonal orientation with the parish. It is important to note that there are areas that are seen as neither suitable nor unsuitable, but that does not necessarily mean that crops cannot be grown in these areas. It just means that, with other factors constant, there is a higher chance that crops grown within the suitable area will produce a larger yield given the average rainfall. It is also interesting to note that the one area that tends to remain in the middle of the extremes of suitable and unsuitable is the center of the parish.

Estimated suitable and unsuitable land areas were calculated for the selected crops, in order to understand which crops had the most available land area for suitable growth in the parish of St. Elizabeth. Figure 52 shows how crops such as tomato, horse, and sweet cassava possess the largest range of suitable growth area. Conversely, Figure 53 shows that crops such as bitter cassava, ordinary corn, and onion have the largest range of unsuitable growth area. In general, there tends to be a much larger amount of unsuitable land area than suitable land area. Figures 52 & 53 were compared to understand which crops had both a large amount of suitable land area and a small amount of unsuitable land area (Figure 54). Again, crops such as tomato, horse, and sweet cassava were among the top candidates for growth in the parish, while bitter cassava, ordinary corn, and onion continued to be ranked near the bottom. This reveals that crops that have a large amount of suitable land area tend to not have a substantial amount of unsuitable area, and vice versa.

By employing the land use map, it can be seen that the northern portion of the parish has fewer land being utilized for farming. This follows well with the findings that there is a general trend of unsuitability in the northern portion of the parish. Thus crop growth is generally more suitable from the center of the parish and towards the coastline, where a majority of the farm land is located.

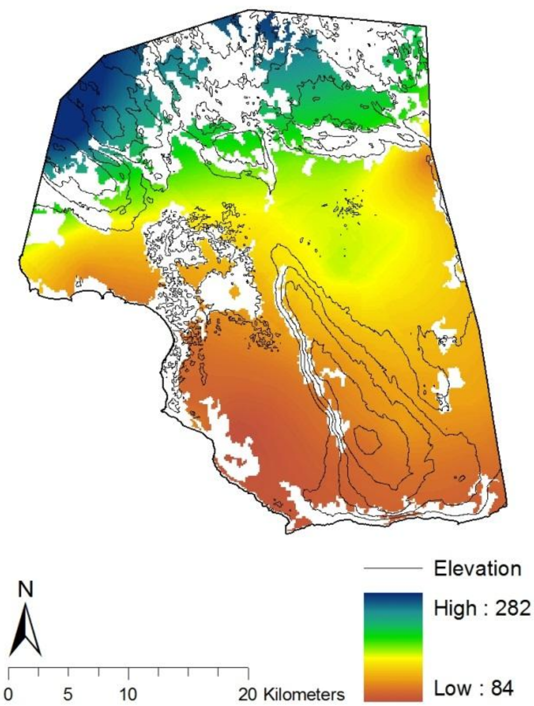


Figure 39. Interpolated annual rainfall over designated farm locations.

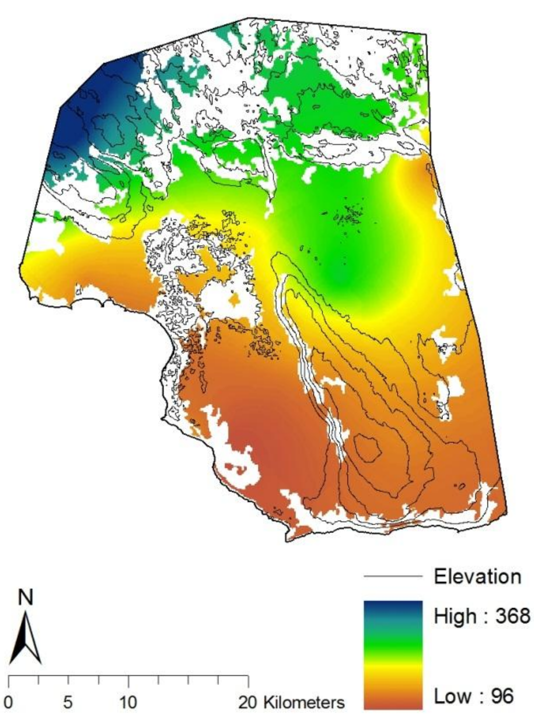


Figure 40. Interpolated early season rainfall over designated farm locations.

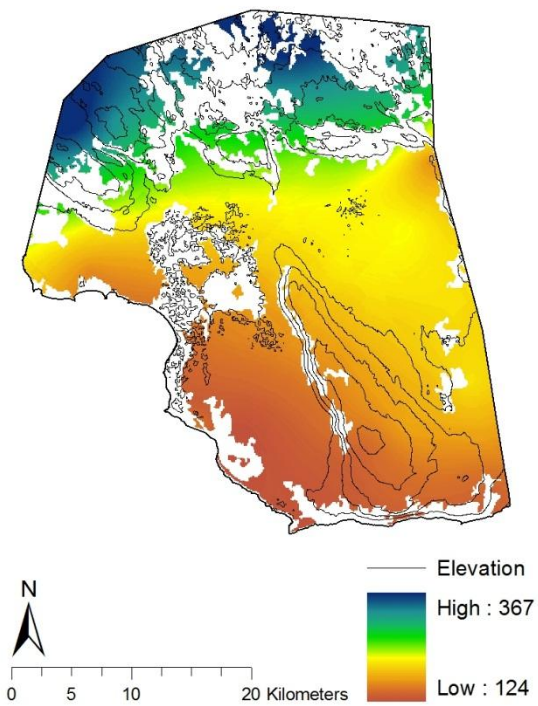
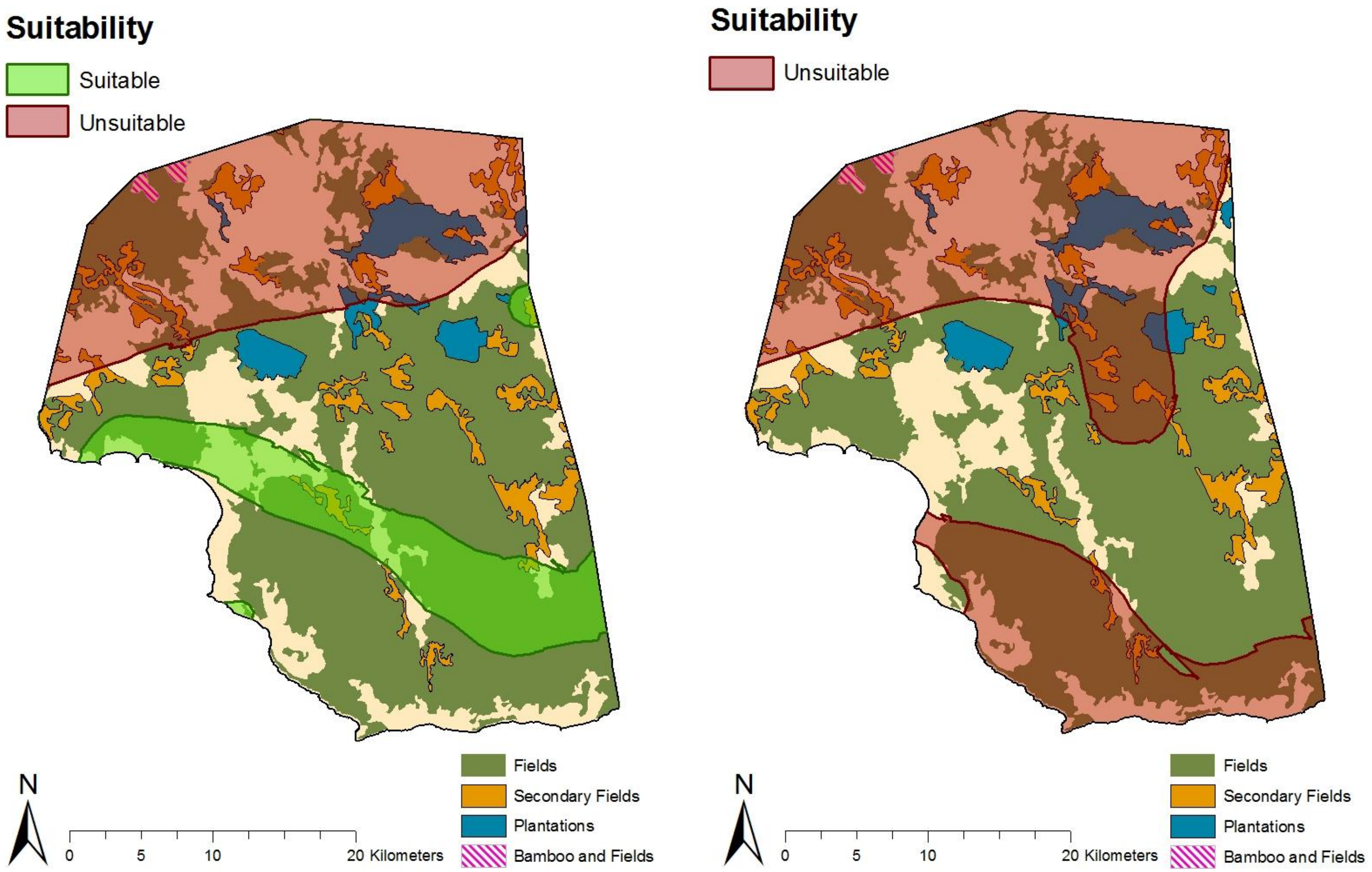
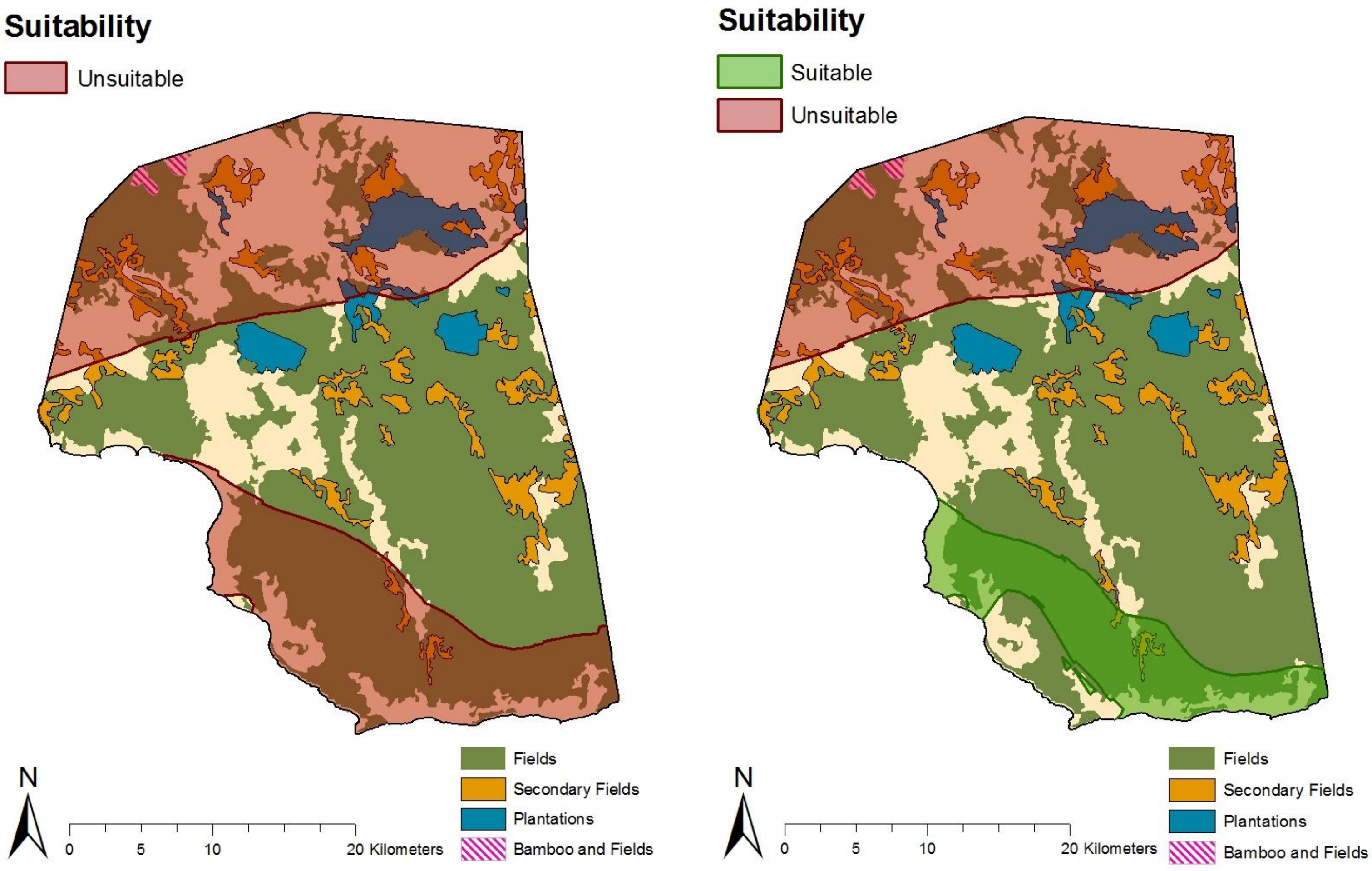


Figure 41. Interpolated late season rainfall over designated farm locations.



Figures 42a and b. Suitability of ordinary corn for annual and early season rainfall.



Figures 43a and b. Suitability of onion for annual and late season rainfall.

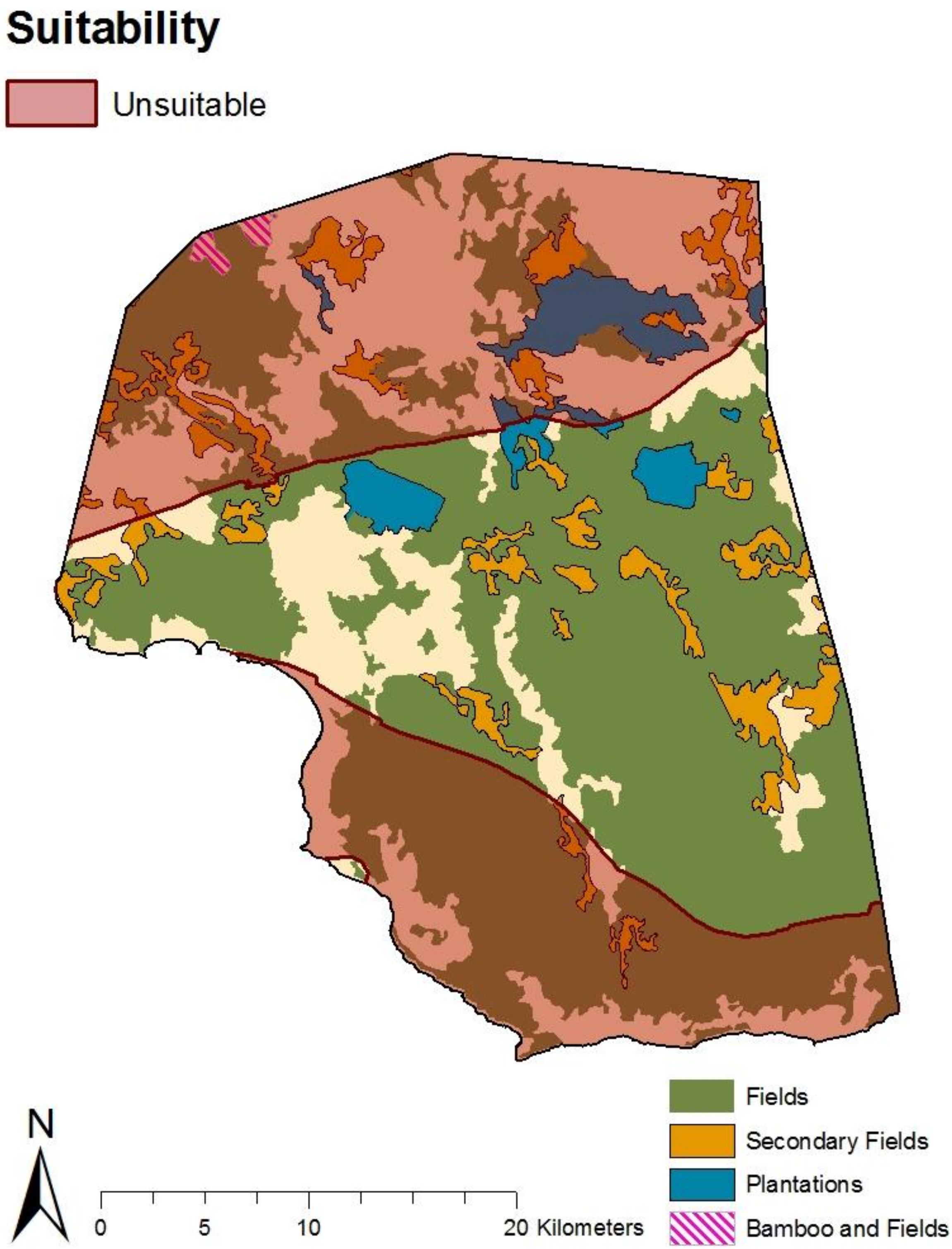
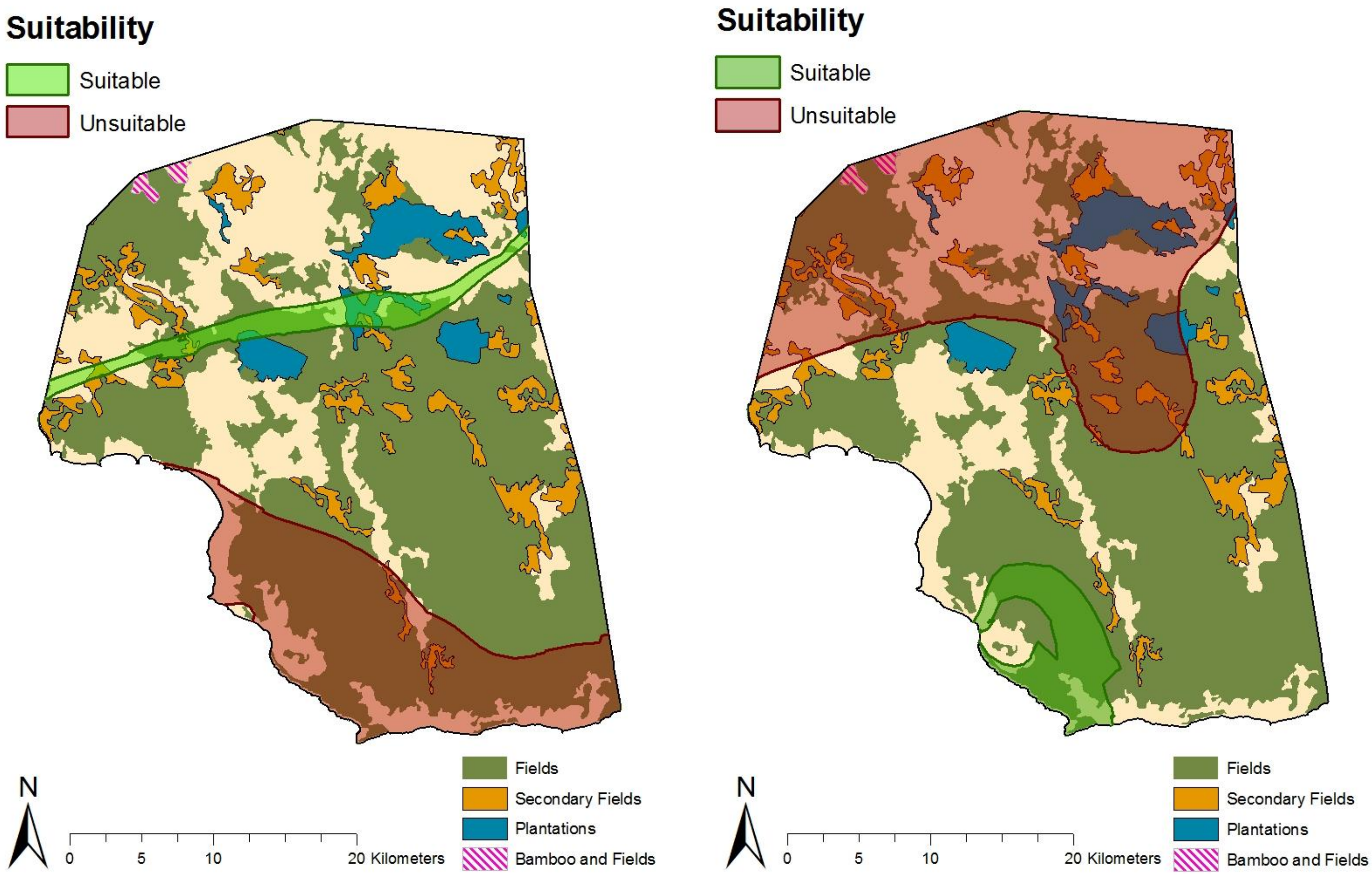


Figure 44. Suitability of watermelon with annual rainfall.



Figures 45a and b. Suitability of cow peas for annual and early season rainfall.

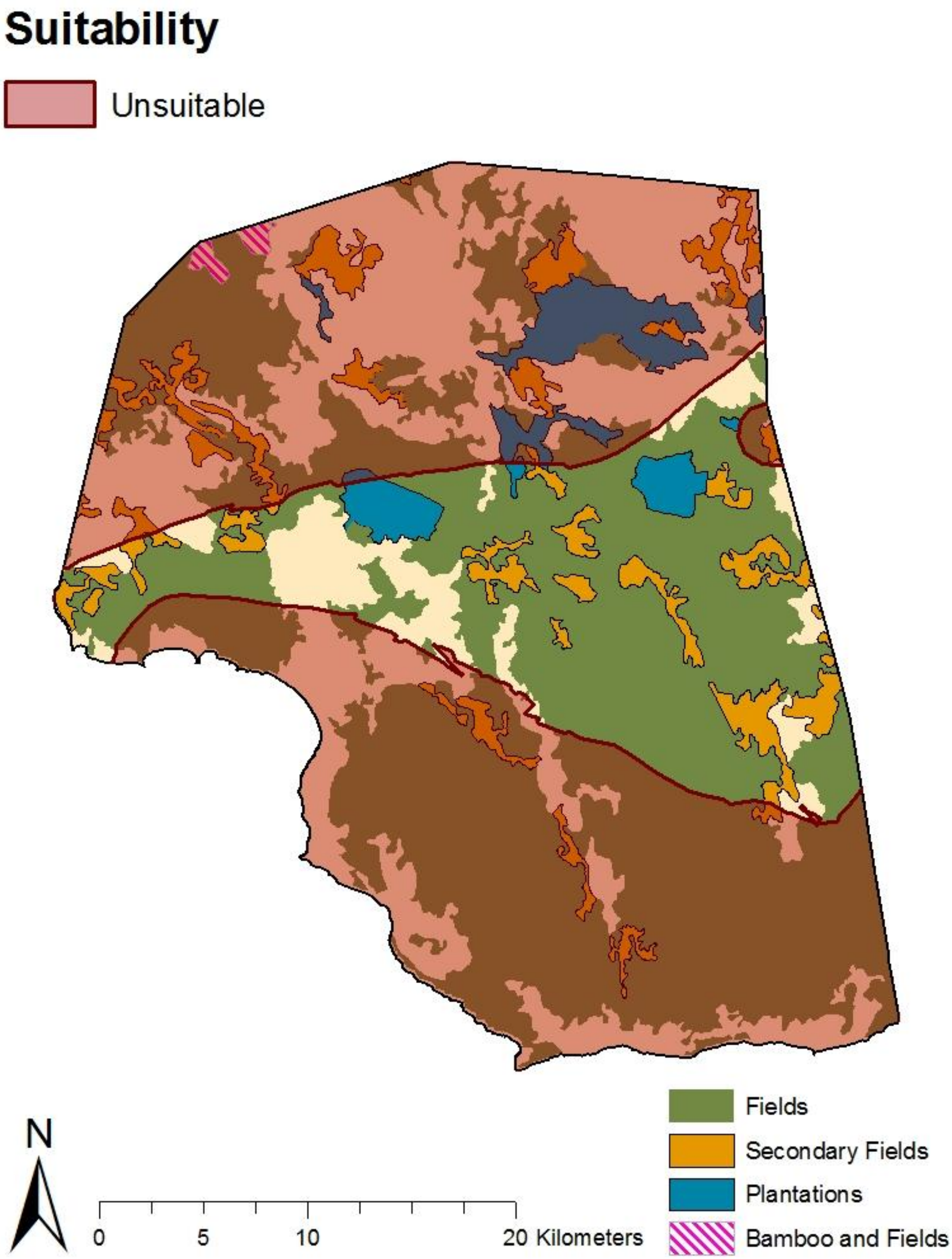


Figure 46. Suitability of bitter cassava with annual rainfall.

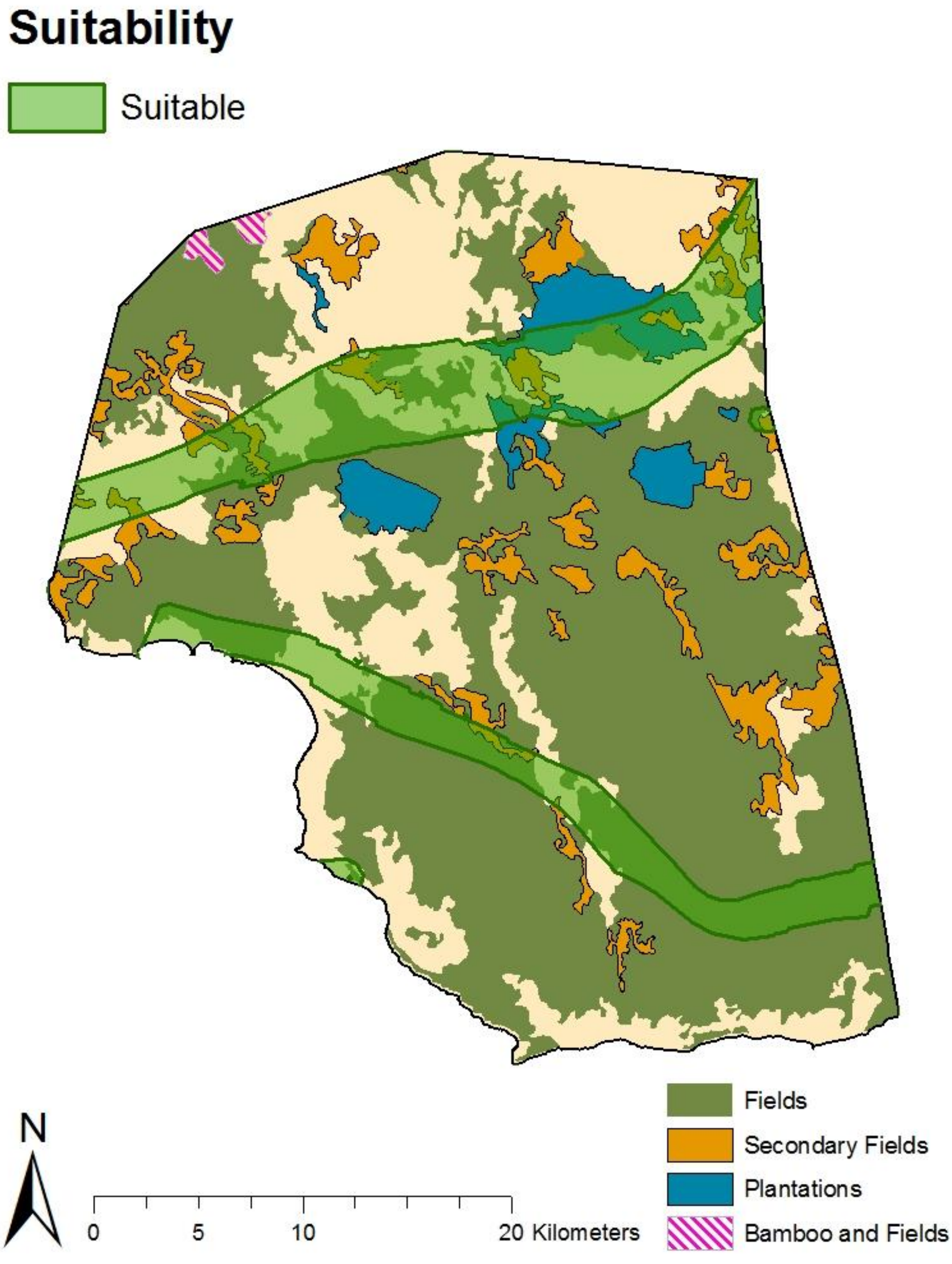


Figure 47. Suitability of sweet cassava with annual rainfall.

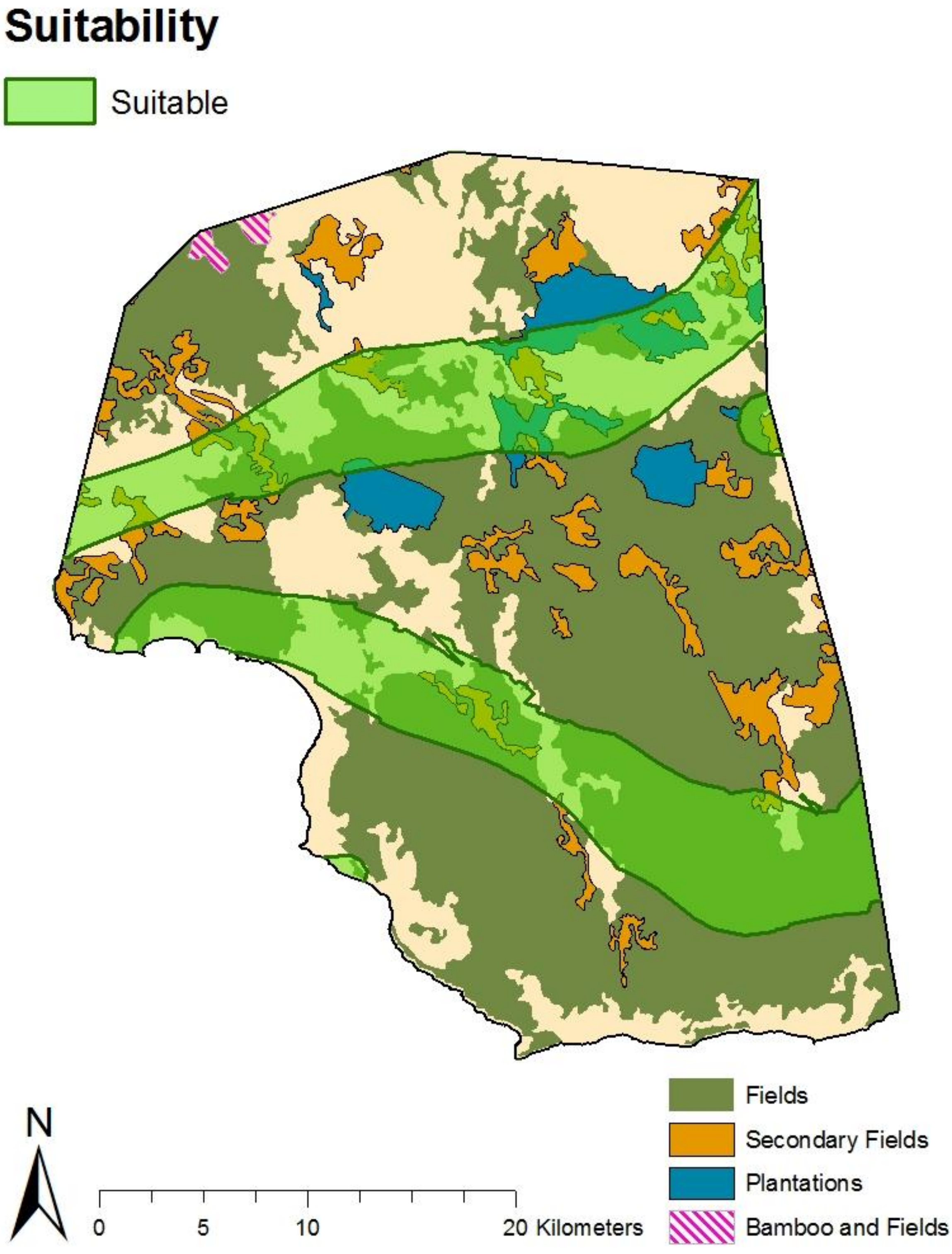
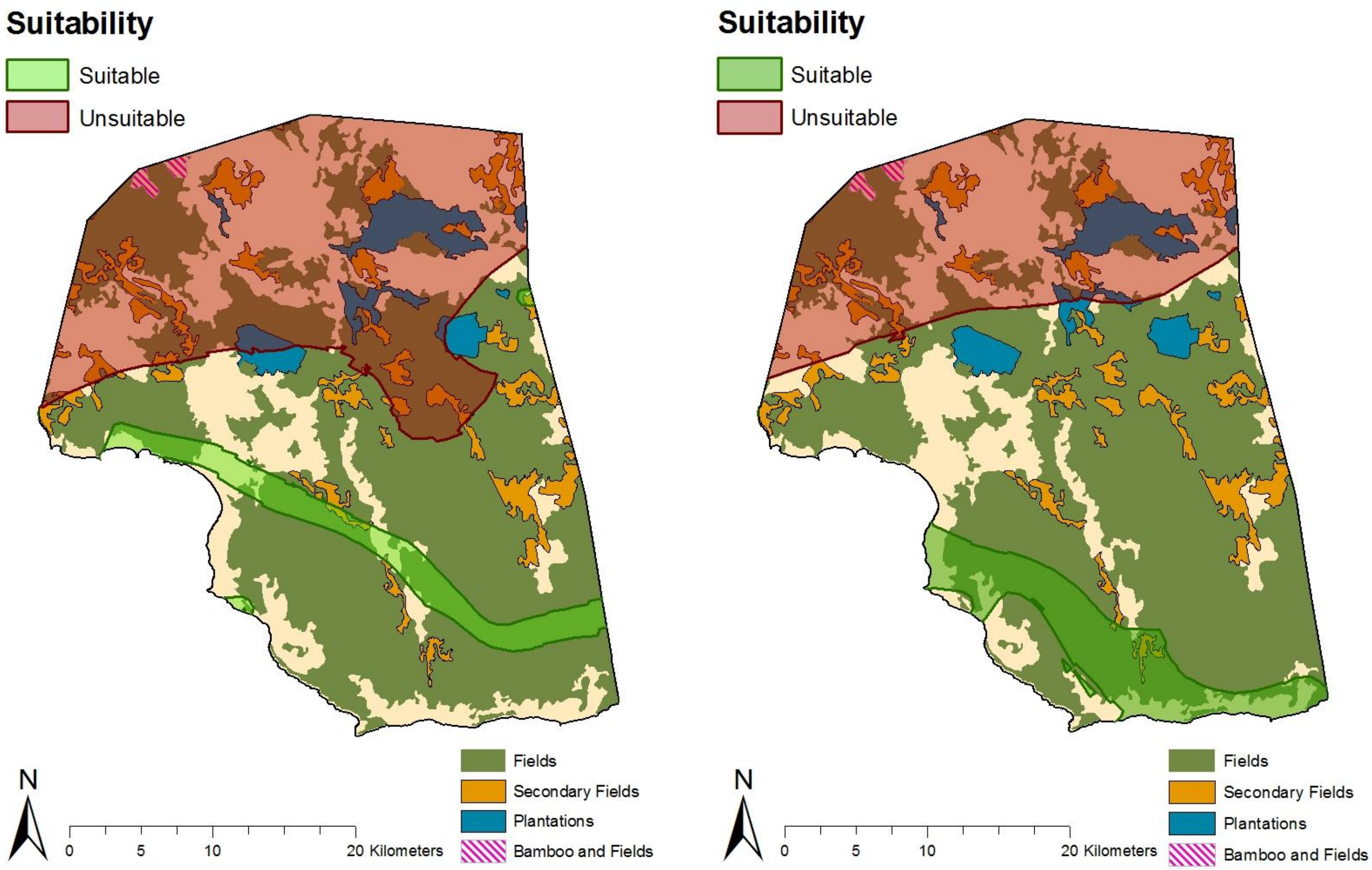


Figure 48. Suitability of horse with annual rainfall.



Figures 49a and b. Suitability of cauliflower with annual and late season rainfall.

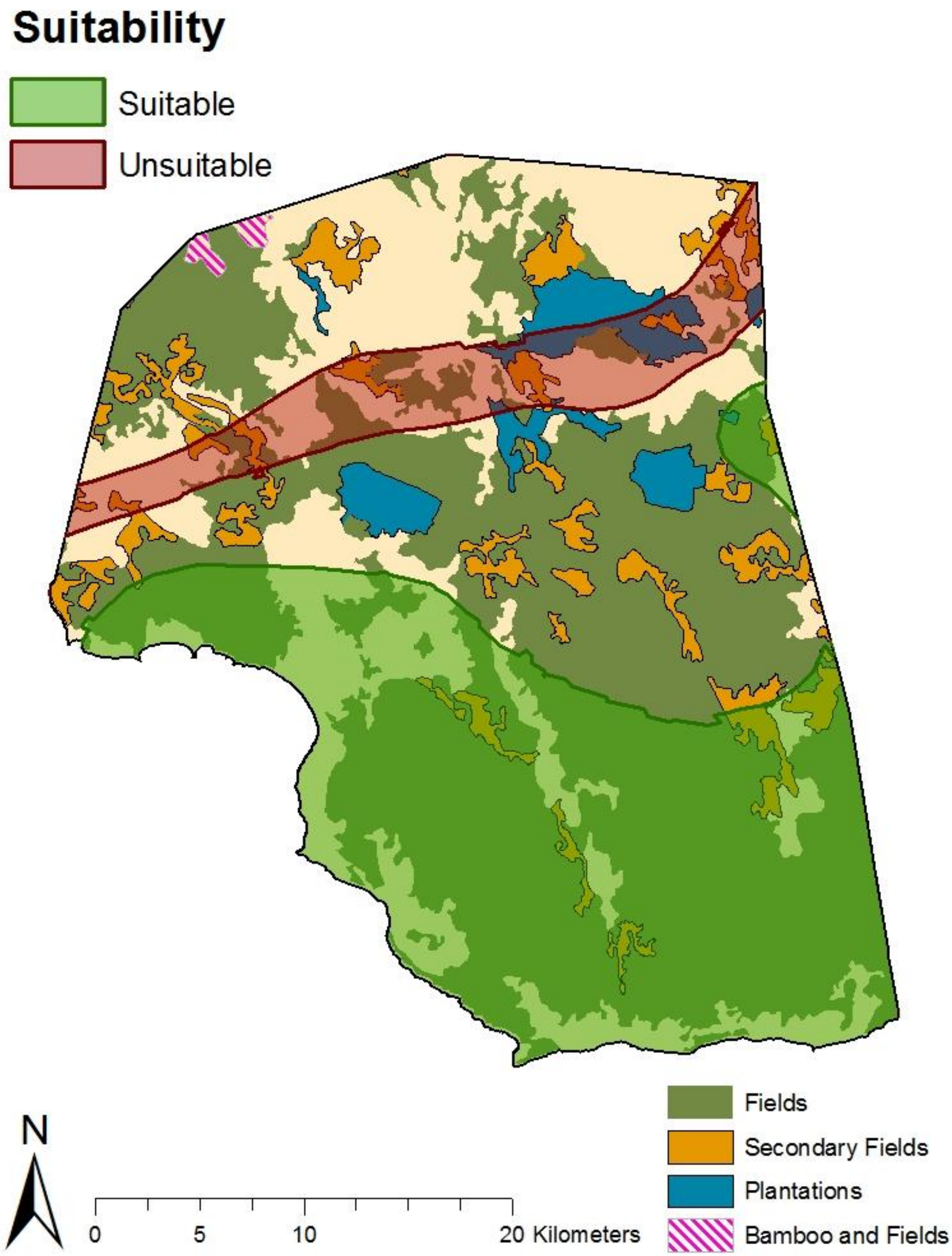


Figure 50. Suitability of tomato with annual rainfall.

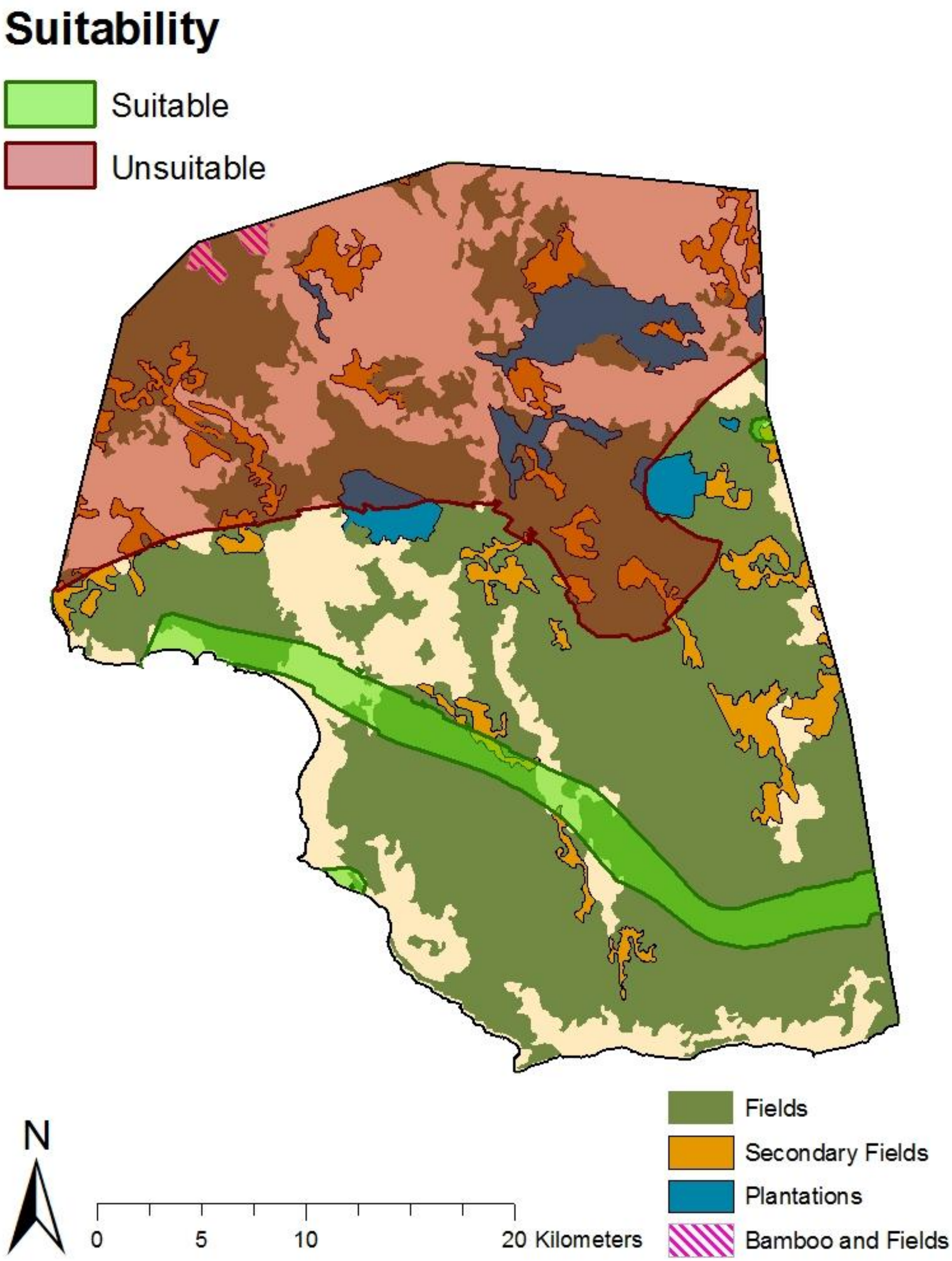


Figure 51. Suitability of yams with annual rainfall.

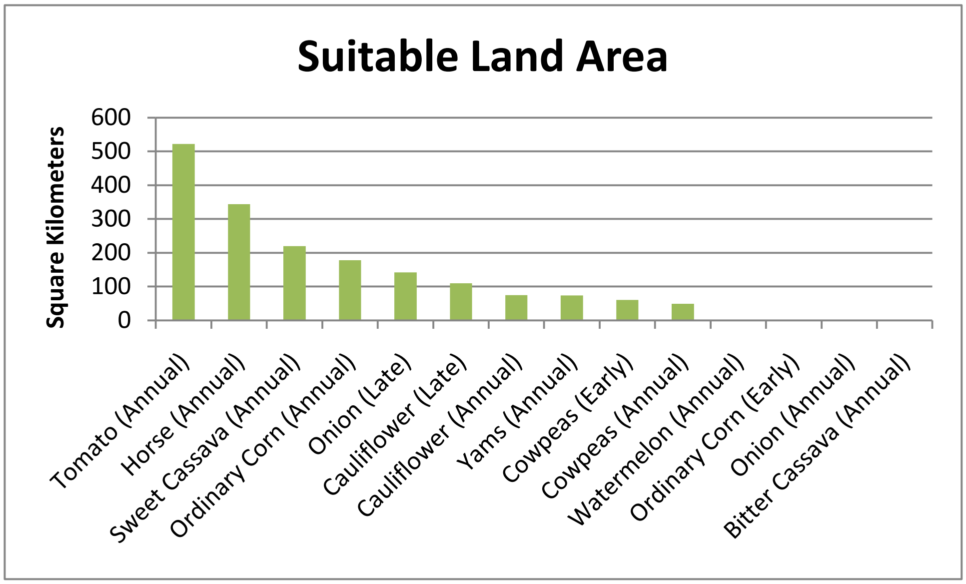


Figure 52. Suitable land area for selected crops.

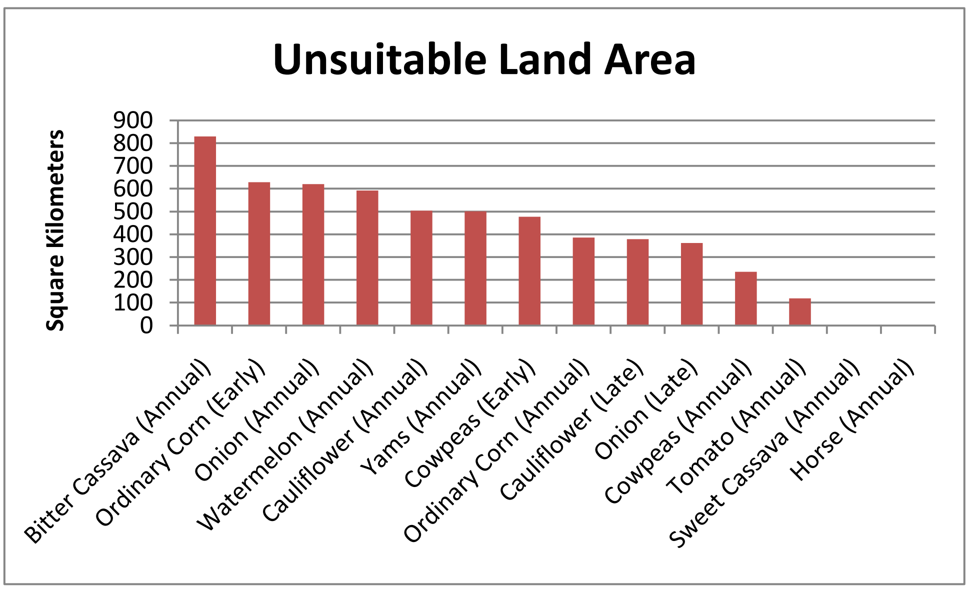


Figure 53. Unsuitable land area for selected crops.

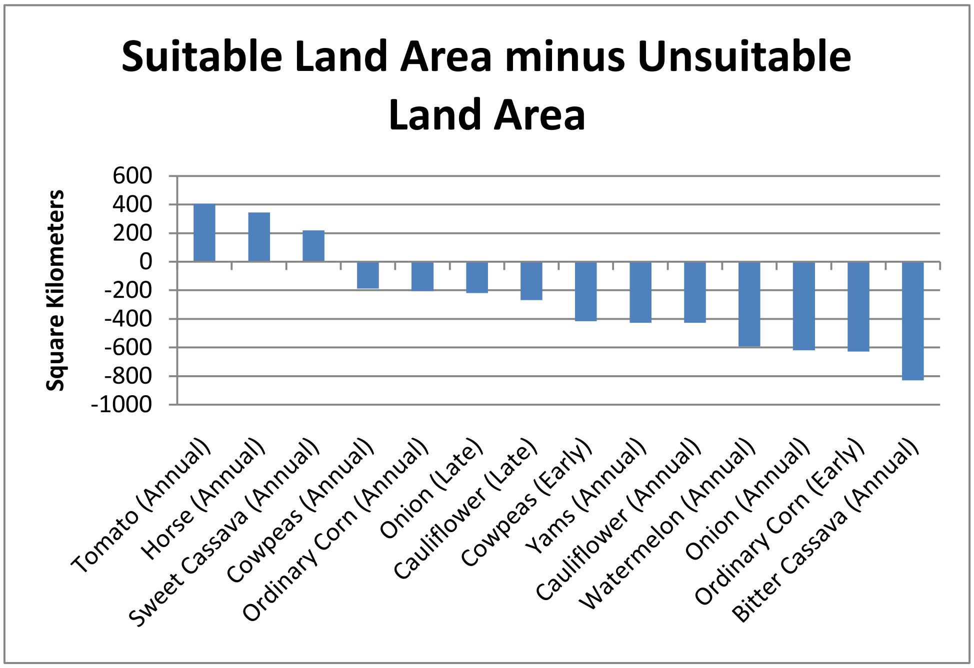


Figure 54. Suitable land area minus the unsuitable land area for selected crops.

Tasseled Cap

Once the preprocessing of the data and imagery has been completed, the Tasseled Cap Transformation can be run on the five monthly mosaicked images. The saved imagery can then be opened within ArcGIS in order to produce maps for Brightness, Greenness and Wetness. An attempt was made to remove the cloud cover and shadows from the images by excluding the values they were associated with. This was done in order to focus on the changes in the parish itself.

Figure 55 illustrates the brightness for St. Elizabeth from May-September 1987. The highest reflectance values indicate the location of bare land or drier vegetation. A change can be seen moving through the MSD period, showing an increase in brightness in the southwest during July and then becoming darker in August. If the land use map were overlaid, it could be seen that these brighter areas align with known farm locations (Figure 14). The topography of the parish indicates a slight ridge in the center of the parish producing a strip of lower brightness values.

The greenness index for St. Elizabeth is presented in Figure 56. The healthy, green vegetation is shown as the lightest features. Thus it can be seen that the healthiest vegetation is in the northern portion of the parish. A fluctuation in greenness can be seen progressing from May to August. There is a decrease in greenness, or healthy vegetation especially from June to July, which then begins to rise again transitioning into August and September. This is a good indication of the MSD's effects on crop growth.

The final layer from the TC transformation can be seen in Figure 57. This images show wetness which indicates soil or surface moisture. The images depict low moisture content in the locations that were designated as having the highest brightness factors. In other words, the areas with the barest land/agriculture also have the lowest moisture. The MSD can also be seen in the wetness band, showing a decrease in moisture from May through July and then an increase from August to September.

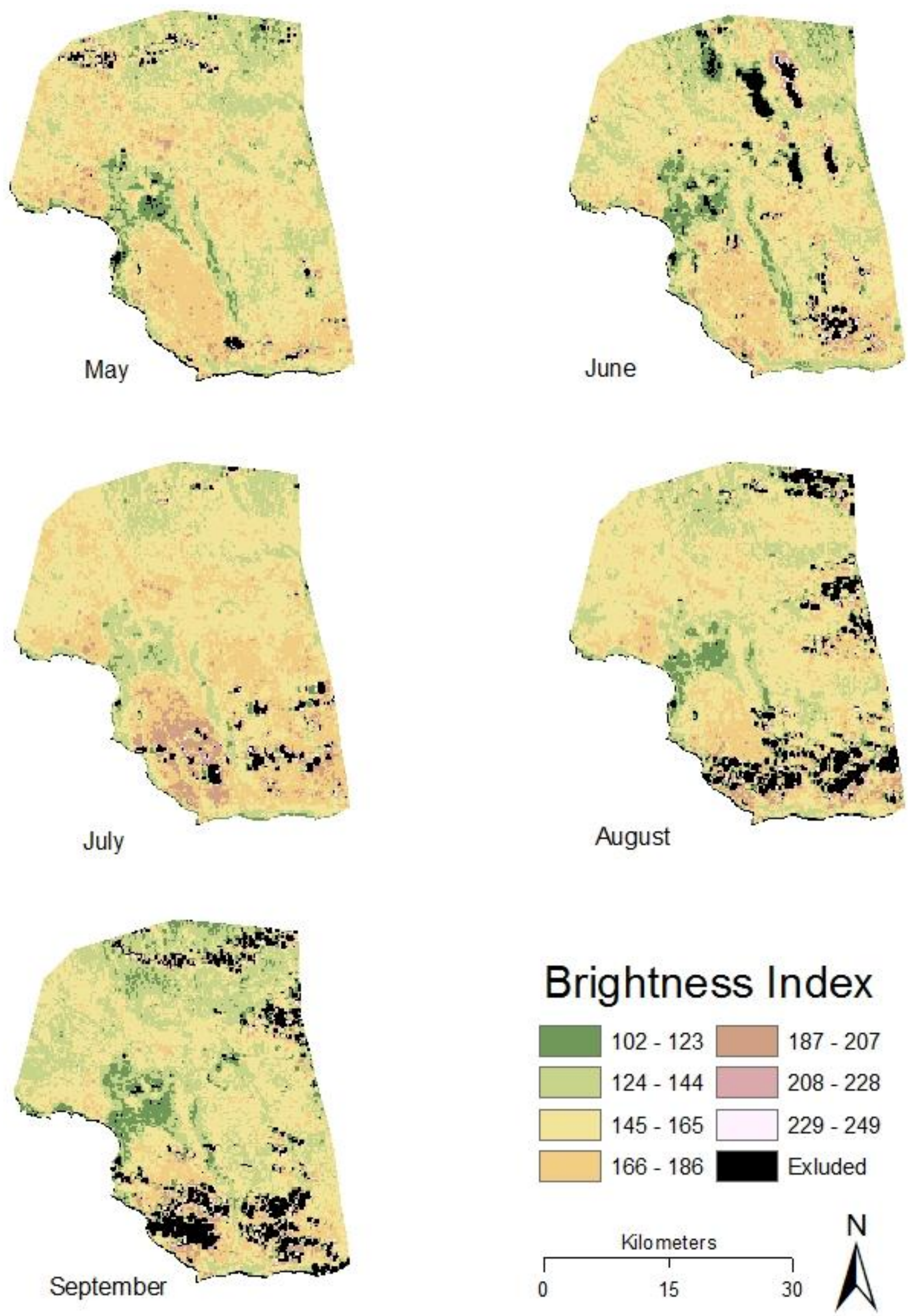


Figure 55. Brightness Images for May through September 1987 for St. Elizabeth, Jamaica.

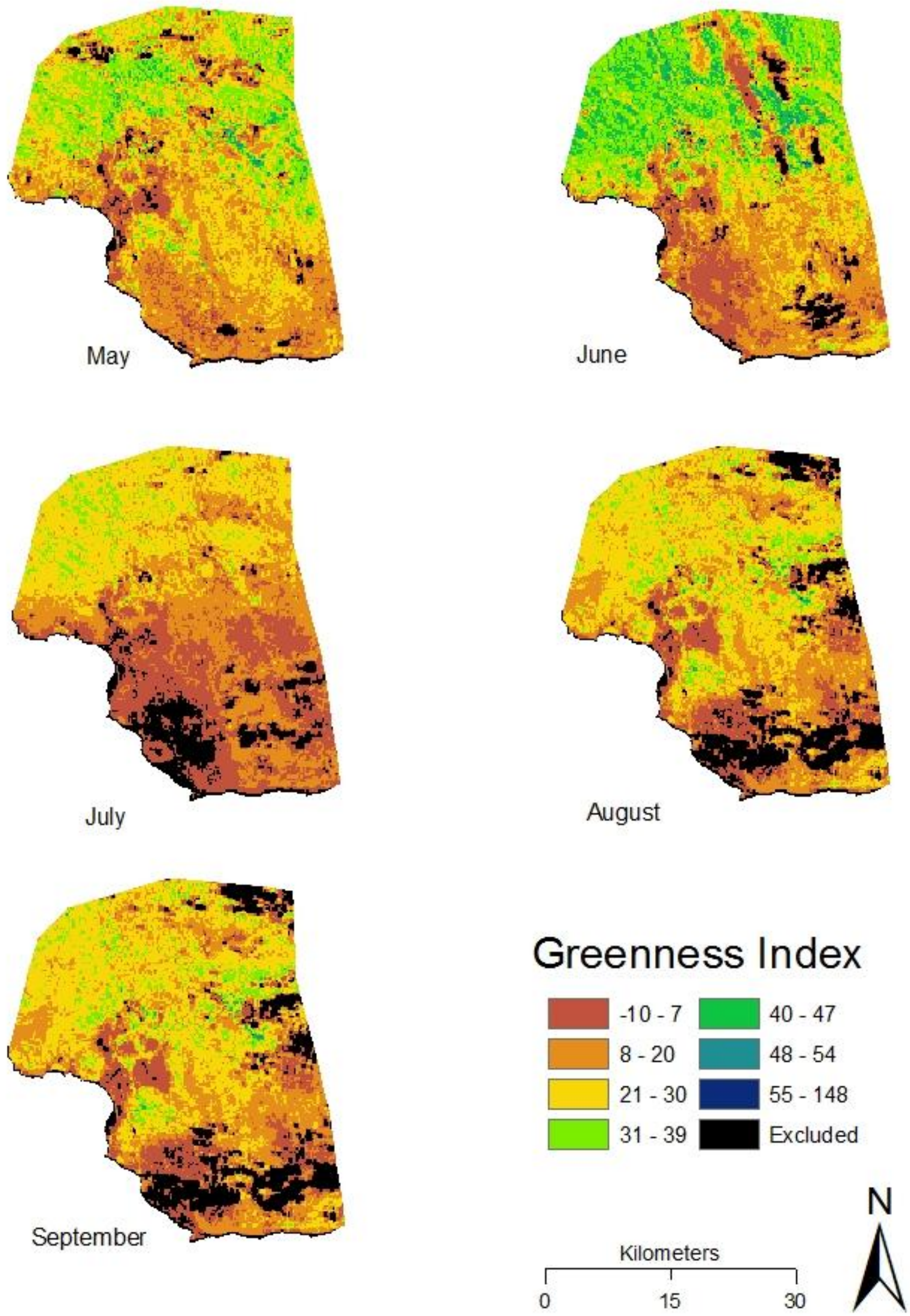


Figure 56. Greenness Images for May through September 1987 for St. Elizabeth, Jamaica.

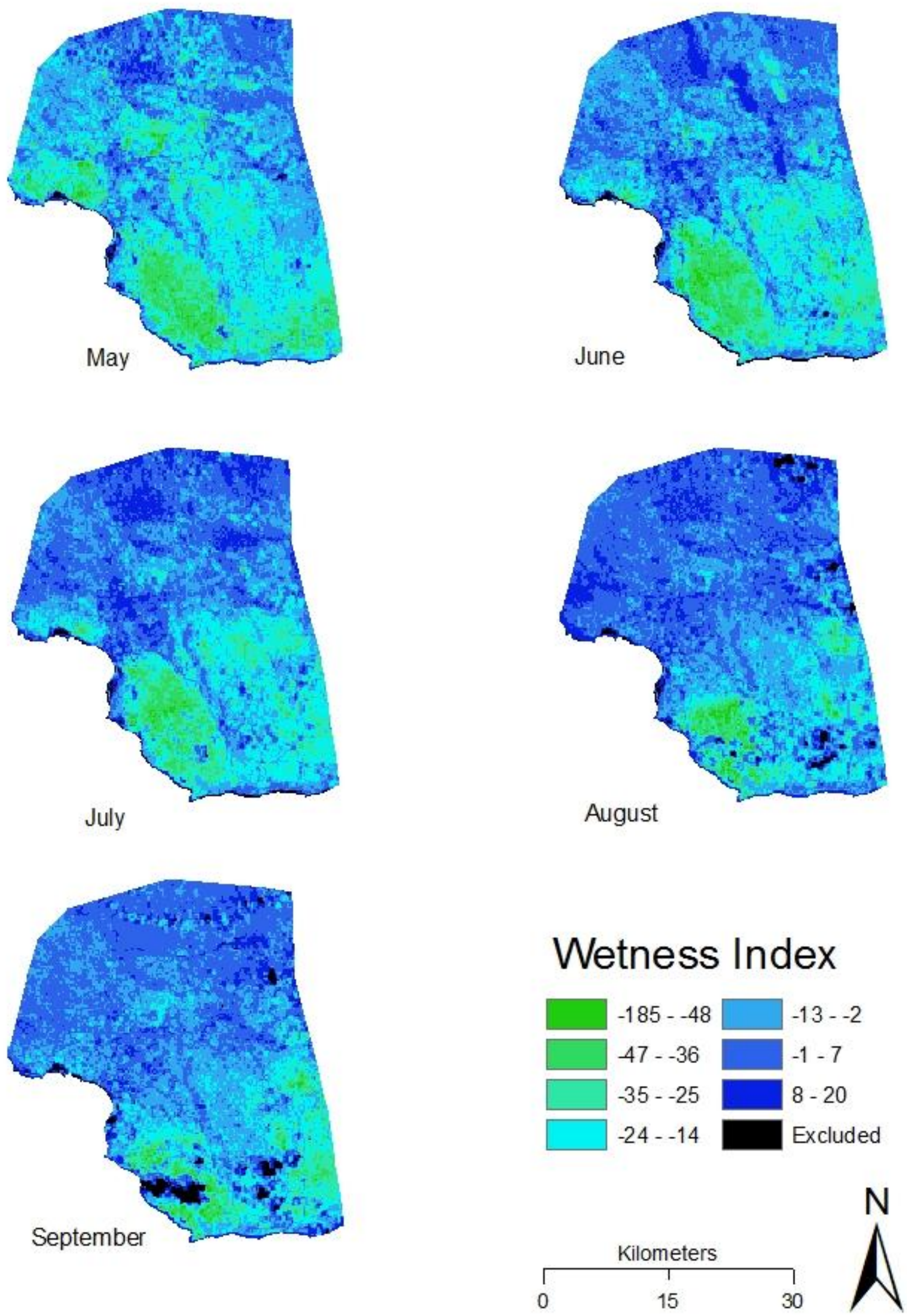


Figure 57. Wetness Images for May through September 1987 for St. Elizabeth, Jamaica.

In order to understand the patterns within the TC transformation, the rainfall from the western portion of Jamaica from 1987 is examined. Figure 58 illustrates the average rainfall that fell within the western portion of Jamaica where the parish of St. Elizabeth is located. The rainfall rises several times, twice during the early rainfall season period and once during late season rainfall. There is also a pronounced dip in rainfall moving from June into August; the MSD period. Figure 59 depicts the crop yield totals for 1987 in tons per hectare.

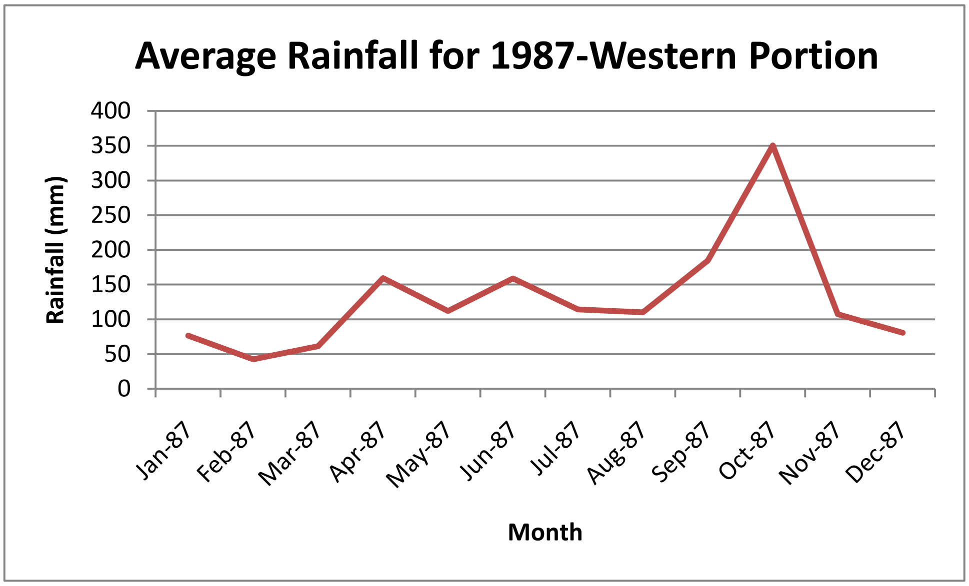


Figure 58. Average rainfall over western portion of Jamaica for 1987.

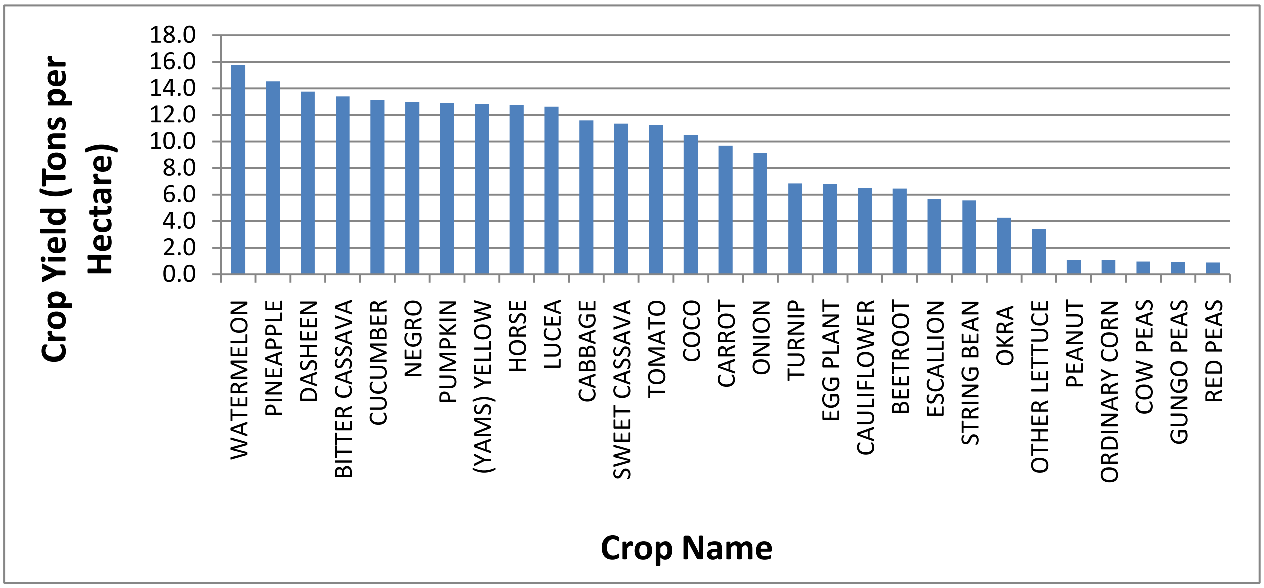


Figure 59. Crop yield in tons per hectare for 1987.

Figures illustrate the difference maps for Brightness, Greenness and Wetness in order to demonstrate the change over time. Again an attempt was made to remove the cloud cover and shadows from the images by excluding the values associated with those features. Since they are difference maps, twice as much cloud cover can be seen in many of the images because the differences take into account both months' images.

The brightness difference images (Figure 60) show the change from May to September. Throughout most of the months, there is a greater amount of negative brightness values. This indicates that there is less bare earth. The most prominent difference is between June and July. A large portion of the parish has an increased brightness index illustrating that there is more bare earth and higher reflectivity during this time period.

Figure 61 illustrates the greenness difference images. From May to June there is a higher amount of greenness occurring in the north compared to the southern portion of the parish which consists of negative greenness values. Between June and July there is a significant decrease in the level of greenness throughout the parish, this aligns with the level of brightness, thus indicating the passing of the MSD. An increase in greenness is then seen moving out of the MSD period, with the exception of the northwest portion of the parish, followed by a leveling out of greenness values from August to September.

The difference of wetness between May and September are illustrated in Figure 62. It can be seen that between May and June there is a higher index of wetness in north and it is drier in the southern plains. Moving into July, the wetness index indicates a more neutral, even slightly positive period. From July to August, there is an increase in wetness in south central St. Elizabeth, with slightly negative and neutral values to the north and south. It is interesting to note that between August and September there is actually a significant decrease in wetness. This indicates that wetness may not be a good indicator of the MSD.

The TC difference maps can be compared to the rainfall difference maps calculated earlier (Figures 32-35). In both sets of images, the MSD is clearly visible moving through the time period, thus proving that the TC transformation is a useful tool for indicating change such as the MSD. Furthermore, the TC resolves small scale variations and differences that weren't visible by viewing the rainfall alone.

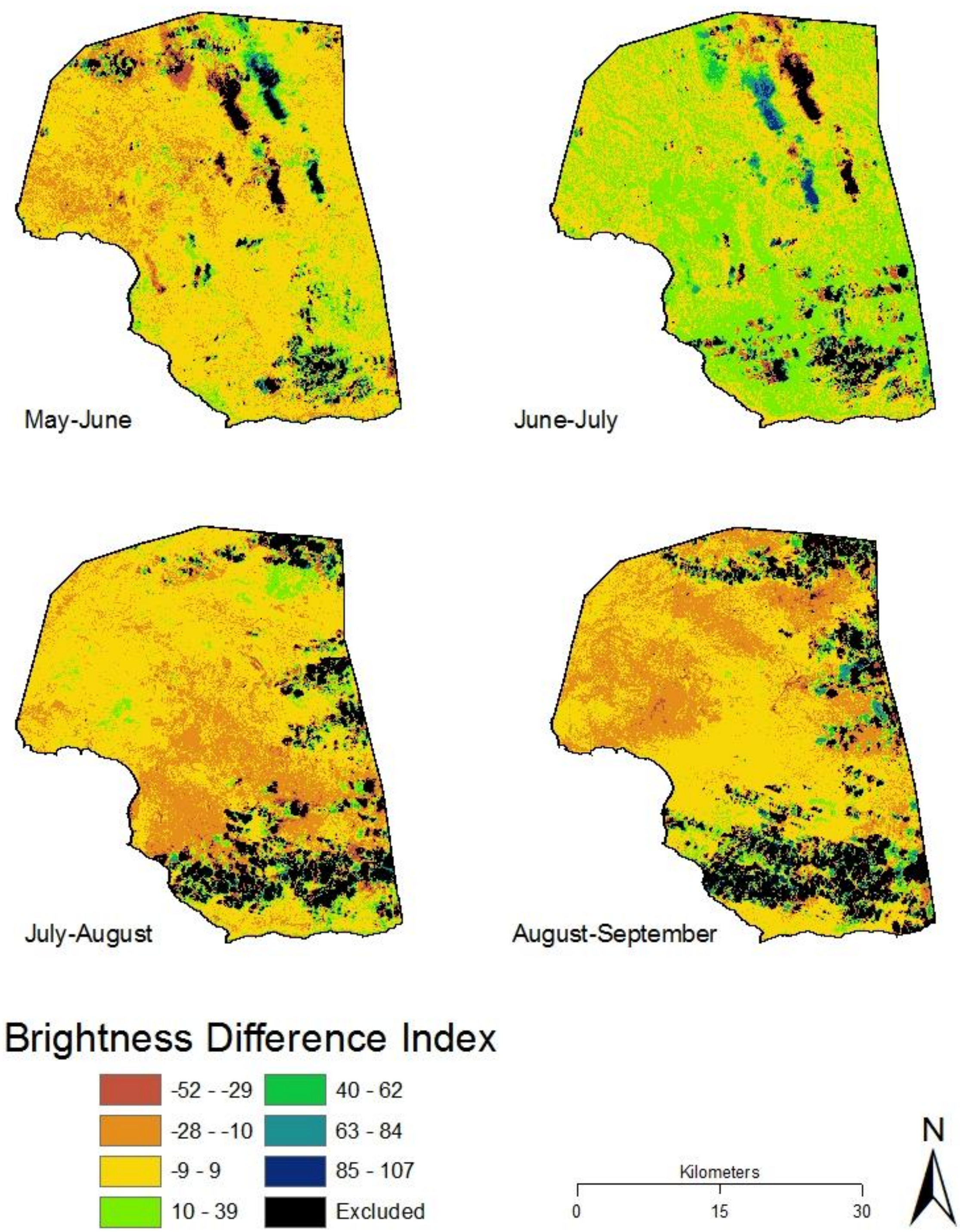


Figure 60. Brightness difference images for May through September 1987 for St. Elizabeth, Jamaica.

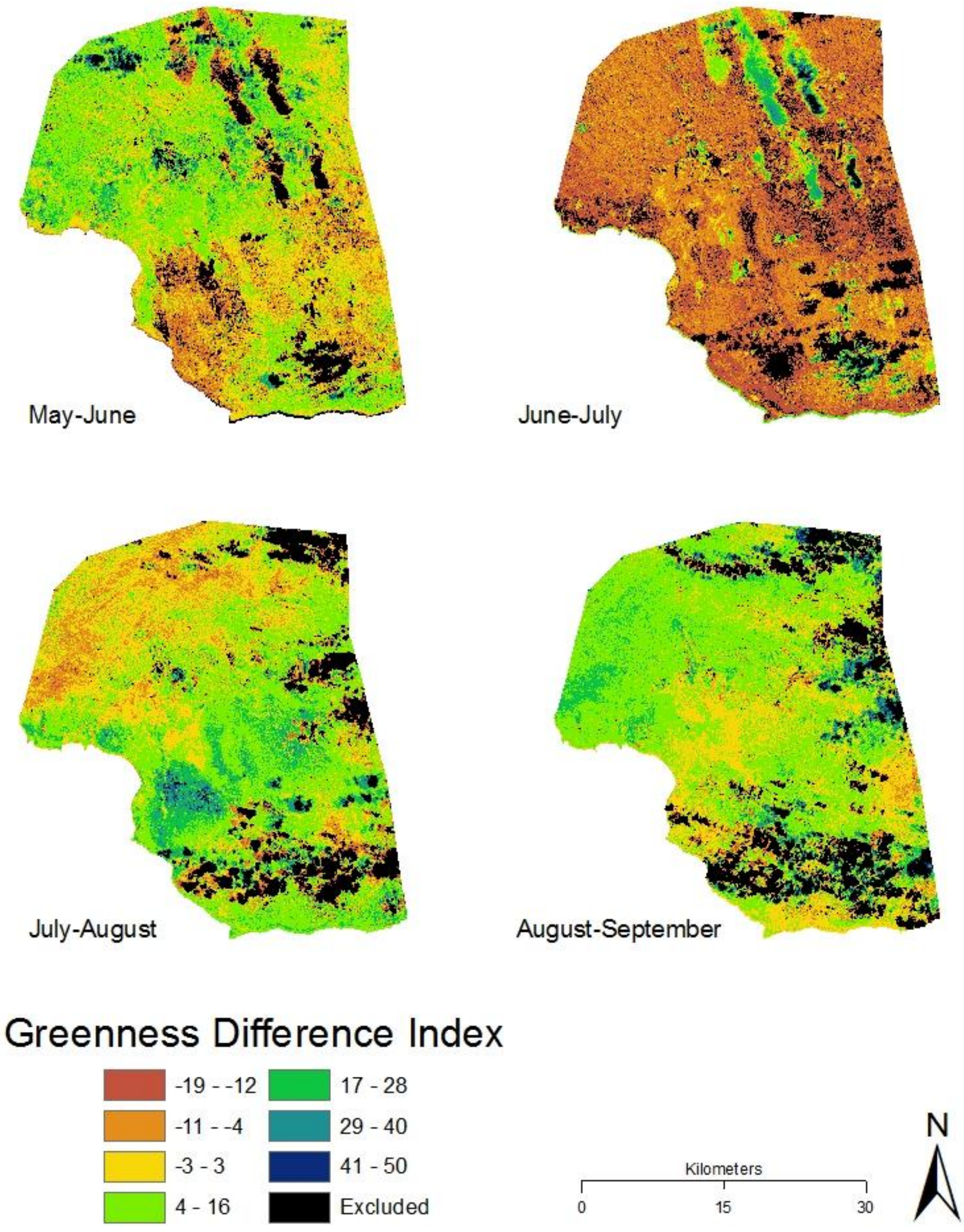


Figure 61. Greenness difference images for May through September 1987 for St. Elizabeth, Jamaica.

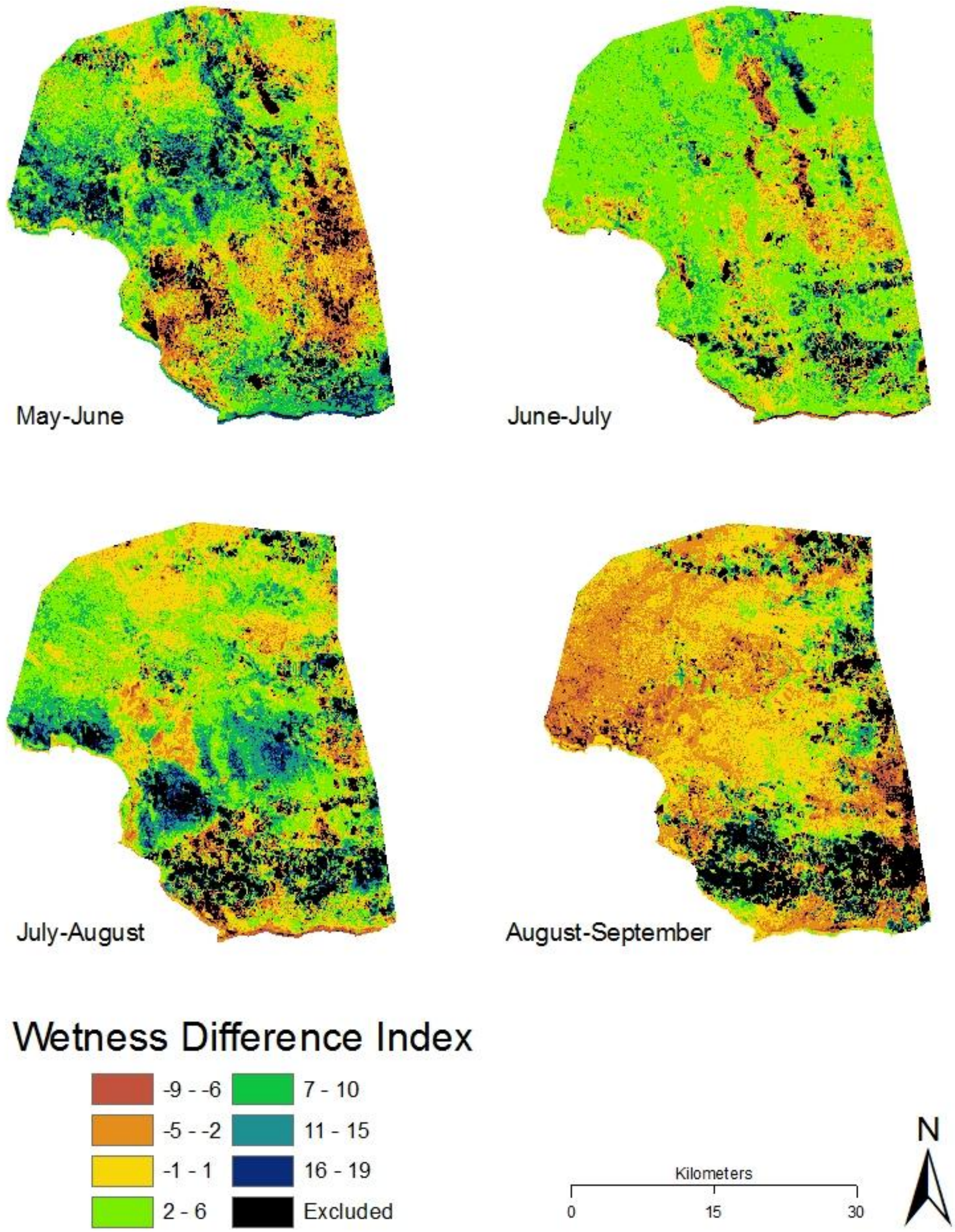


Figure 62. Wetness difference images for May through September 1987 for St. Elizabeth, Jamaica.

Chapter 5: Discussion and Conclusion

Conclusions

In this study, the MSD was examined in order to answer three main questions:

1) What is the effect of the MSD on the production of seasonal crops grown in Jamaica? How does the overall/seasonal crop production vary between 1965 and 2007?

2) Is there an optimal rainfall range for each crop within St. Elizabeth? Are there optimal locations within St. Elizabeth based on land-use and optimal rainfall ranges?

3) What are the impacts of the MSD on the vegetation within St. Elizabeth?

The Mid-Summer Dry Spell (MSD) is an established atmospheric phenomenon that occurs throughout the Caribbean. Although it is not a true drought in the sense of near zero rainfall conditions, the MSD can result in as much as a 40% reduction in rainfall (Magaña et al. 1999, Small and Szoeke 2007). The consequence of this occurrence is a bimodal annual rainfall with a peak in May/June and a second greater maximum in October (Taylor and Alfaro 2005, Magaña et al. 1999).

The first portion of this research was to understand how crop production related to rainfall of Jamaica. Looking at annual, early and late season rainfall there is a wide range of correlations. Some crops have either positive or negative correlations throughout all rain seasons, while others are relatively neutral throughout. The correlations overall depict that rainfall does have a relationship with crop production yet it is not the only factor affecting crop growth, for example socio-economic and other atmospheric factors, such as severe storms.

Examining rainfall within the parish of St. Elizabeth indicated that the MSD can be seen through rainfall amounts. The difference maps solidified this finding by illustrating how the MSD begins in the north during May and recovers one month earlier than the southern portion of the parish, since the southern MSD is one month behind the north. This could definitely impact when and where farmers plant their crops.

Utilizing correlations with crop yield and annual, early, and late season rainfall from 1979-2007, relationships can be determined of how the MSD effects crop production in Jamaica. It is known that crops have certain water requirements for optimal growth and the MSD can have an effect on such requirements. It is hard to determine the exact effect the MSD has on crop growth because these requirements are unknown. Certain crops could require less rainfall while others may need more.

By utilizing the optimal rainfall ranges calculated by the maximum and minimum values for the 10 most and least productive years, suitability maps were created in order to help determine agricultural efficiency within the parish of St. Elizabeth.

Throughout a majority of the suitability illustrations, the areas of unsuitability and suitability seem to follow a general pattern, with either a large unsuitable portion in the north and the south or smaller strips of suitable crop growth. It is important to note that there are areas that are seen as neither suitable nor unsuitable, but that does not necessarily mean that crops cannot be grown in these areas. It just means that there is a higher chance that crops grown within the suitable area will produce a larger yield. It is also interesting to note that the one area that tends to remain in the middle of the extremes of suitable and unsuitable is the center of the parish.

One crop that stood out was tomato. Tomato is a crop grown frequently and in large quantities in St. Elizabeth. The results indicate that tomato had the largest positive correlation with annual and early season rainfall, and had one of the largest areas for suitable crop growth during annual rainfall.

By employing the land use map, it can be seen that the northern portion of the parish has fewer land being utilized for farming. This follows well with the findings that there is a general trend of unsuitability in the northern portion of the parish. Thus crop growth is generally more suitable from the center of the parish and towards the southern coastline, where a majority of the farm land is located.

In a recent study (Ford et. al, 2009), the arable lands of St. Elizabeth were mapped. According to the United States Department of Agriculture (USDA) Land Capability Classification System (LCCS), approximately 18 percent of the lands in St. Elizabeth are arable. Within this system of classification, some farm lands were excluded, if these lands were included, the arable lands could be as high as 26.57 percent. The result of the study was a 2008 land cover/land use map. Of the approximately 32,000 hectares of arable lands, 47 percent is used for the cultivation of intensive mixed agriculture, 15 percent is for sugarcane and 14 percent for pasture. Figure 63 illustrates the distribution of land use. Potential areas of underutilized lands for agricultural expansion were brush and unimproved pasture, which occupies 16 percent of arable land. Several recommendations were stated at the end of the study. One in particular revolved around conducting crop suitability mapping within the arable zone (Ford et al. 2009). This really signifies that the research conducted within this thesis could be expanded and joined with like-minded researchers to develop a more detailed list of crop suitability rules.

Referring back to Figure 14, the land-use map utilized within this research, differences can be noted. The map used for this study was from 1998 and illustrates four types of land-use. In contrast, the more recent land-use/land cover map from 2008 has more detail, including some crop specific land-use information. Comparing the two, it can be seen that there is a drop in land-use for farming from 1998 to 2008. This could be attributed to a couple reasons: farm acreage has decreased in the past decade and the dataset utilized in this study wasn't as detailed as the 2008 study.

Answering the second question, based on the suitability ranges calculated for the island of Jamaica and downscaled to St. Elizabeth, it can be determined that there are optimal ranges of rainfall per crop for optimal crop production. This research also helped to determine that there are also locations within the parish for optimal growth, varying per crop, as well as locations likely unsuitable for crop growth. These conclusions would need to be validated with field work in order to verify that the findings are sound.

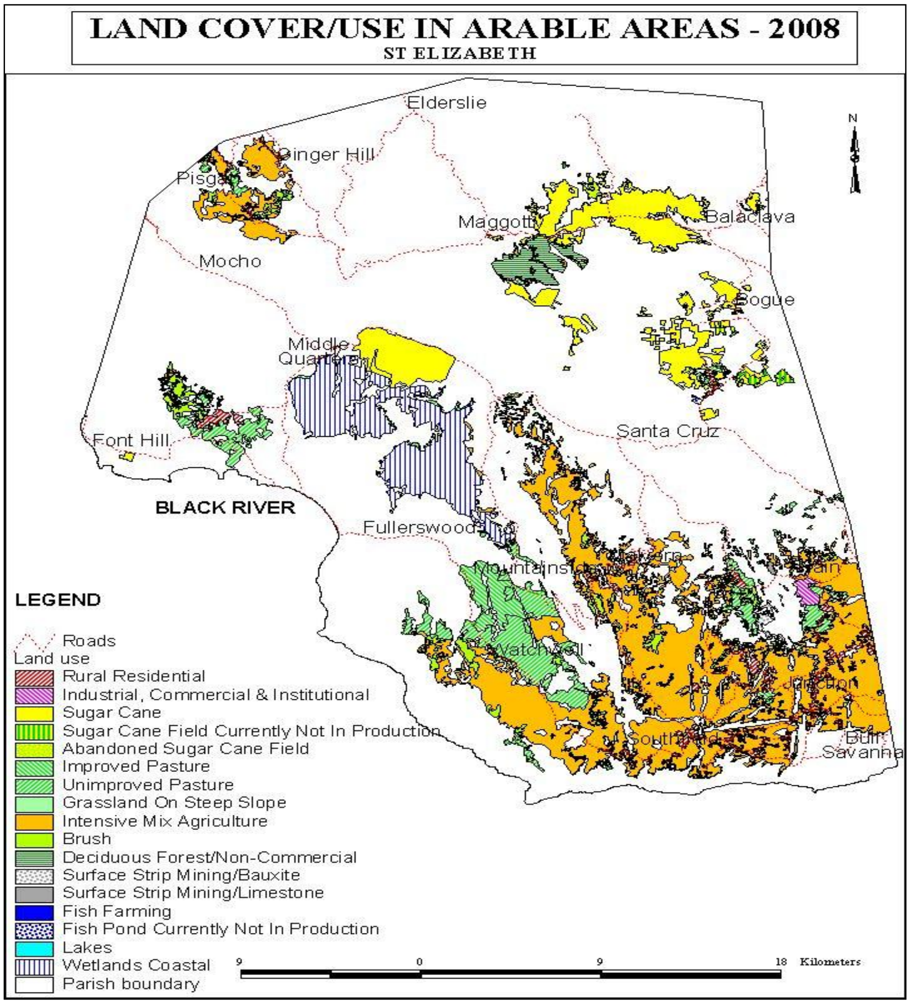


Figure 63. Land cover and land use in arable areas in 2008 for St. Elizabeth, Jamaica, from Ford et al. (Figure 2.1).

The utilization of satellite and aerial imagery plays a significant role in today's agricultural production. The value of this imagery is two-fold. First, the imagery provides important information that is useful for planning and managing potential crop output in a sustainable way. Secondly, the imagery allows local, regional and global scale collection of knowledge about agriculture and forestry. This type of information enables a better understanding of production factors and risk management decisions as well as supports predictive modeling of food supply and consumption. If we can understand how crops are impacted by their environments, we can better understand how to adapt in the future (Thurston, 2011).

Countries all over the world are utilizing such technology, due to the stress on crop production caused by an increase in the world's population. One such company is Satellite Imaging Corporation that provides satellite imagery data at different spatial, spectral and temporal resolutions for research including: agriculture and crop assessment, crop health, change detection, environmental analysis, irrigated landscape mapping, yield determination and soils analysis (Satellite Imaging Corporation).

Employing such remote sensing technologies such as the utilization of Landsat imagery and the TC transformation are important for looking at how vegetation changes over a time period. The last part of this research was to understand how the MSD impacts brightness, greenness and wetness of the land and vegetation within St. Elizabeth. Utilizing Landsat imagery from 5 months around the MSD month, monthly maps and difference maps were created using the TC transformation. The figures indicated a change, illustrating a clearly defined MSD moving through the parish, with brightness and greenness indicating a strong change compared to wetness. The MSD was proven to have a positive impact on brightness and a negative impact on greenness. Further analysis of different years could help to determine whether the wetness index plays a significant role in determining the MSD or if it does not.

Discussion

Limitations

There were many limitations of this research that did not allow for optimal results. One of the largest issues dealt with the original data itself. Jamaica does not have a solidified weather station collection system such as the one found in the United States run by the National Weather

Service. This meant that finding data for a certain time period could be hard due to breaks in data. Temperature data was inadequate, so the focus was placed upon rainfall and crop yield.

Another issue that arose was the use of two different rainfall datasets, one for Jamaica and a second for the parish of St. Elizabeth. The first dataset was acquired from GPCP, a satellite derived dataset; which could have some error involved. The second rainfall dataset was acquired from rain gauges spread across St. Elizabeth. It is also important to note that while there are comparisons being made throughout this research, there is a mismatch in the time series between the datasets being used. These include: GPCP rainfall (1979 to 2007), St. Elizabeth rain gauges (30 year mean, 1951 to 1980), Crop production (1965 to 2007), Land use (1997), and Landsat imagery (1987).

Determining which Landsat images to use for research proved to be difficult during the downloading process. It was a challenge to find 3-4 months of data around the MSD month, July, with minimal cloud cover that would affect analysis. Since Jamaica is located in the tropics, clouds are a common occurrence especially during the summer months.

An additional problem that arose was that the parish of St. Elizabeth was located between two row paths of the satellite. Thus instead of only 5 images, there ended up with a total of 10 images that had to mosaicked together in order to get one cohesive image of the parish.

Future Research

The research conducted in this thesis can be further refined. It is important that this research is continued on crop growth and the MSD in Jamaica. Further research could include an in-depth analysis of when and where certain crops are grown within Jamaica and St. Elizabeth. A new land use map could be created from the findings and include more details about what is being grown and where.

An important aspect of Jamaican rainfall-crop growth research that needs to further develop is that of available data. With a lack of data and information at the local scale, further data collection is needed. Stations could be set up to allow for both temperature and precipitation measurements, in order to make calculations and assessments more accurate at the local level. A trip was recently taken in order to set up two rain and several temperature gauges at known farm locations. With future funding, more stations can be set up to ensure more data is acquired.

The same TC transformation analysis should also be conducted over several different years to see how they differ. Certain years could have more severe droughts or have had more rainfall from passing storm systems, which could skew the results.

If all the data can align in the same year and time period, the results would be more reliable. Thus in order to acquire the specific Landsat imagery for the Tasseled Cap transformation, a special trip would need to be taken in order to ensure that imagery is collected for the required months and with optimal clear skies.

Through the utilization of several techniques, as well as qualitative and quantitative research methods, the answers to the above stated questions were successfully found. While these questions were answered, more have definitely arisen and further research will be required to expand upon these findings. In a world where the population is booming, agricultural efficiency and the management of crop growth is more important than ever. The more we understand how climate, atmospheric conditions and socio-economic factors affect the way crops are produced, the better we more efficient we can become and the more crops we can be cultivated.

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APPENDIX A: OPTIMAL RAINFALL RANGES PER CROP FOR ANNUAL, EARLY and LATE SEASON RAINFALL FOR JAMAICA

Annual Rainfall (mm)

	Most Productive			Least Productive		
	Min	**Max**	**Range**	**Min**	**Max**	**Range**
Beetroot	106	162	55	122	198	75
Bitter Cassava	122	162	40	106	198	91
Cabbage	127	198	70	106	158	52
Carrot	127	198	70	106	162	55
Cauliflower	106	154	48	113	198	85
Coco	122	198	76	106	168	62
Cow Peas	106	173	67	105	162	57
Cucumber	122	162	40	106	198	91
Dasheen	122	162	40	106	198	91
Egg Plants	122	173	50	113	168	56
Escallion	127	198	70	113	173	60
Gungo Peas	122	168	47	106	198	91
Horse	106	198	91	122	162	40
Lucea	122	154	32	106	198	91
Negro	106	168	62	113	198	85
Okra	113	173	60	122	162	40
Onion	106	168	62	105	198	93
Ordinary Corn	106	168	62	122	198	76
Other Lettuce	113	173	60	106	198	91
Peanut	113	173	60	106	198	91
Pineapple	122	158	36	122	198	75
Pumpkin	122	198	76	106	158	52
Red Peas	106	198	91	122	162	40
String Bean	113	173	60	106	198	91
Sweet Cassava	106	198	91	113	168	56
Tomato	133	198	65	113	173	60
Turnip	113	173	60	106	198	91
Watermelon	106	168	62	105	198	93
Yams (Yellow)	106	154	48	113	198	85

	Early Season Rainfall (mm)					
	Most Productive			Least Productive		
	Min	**Max**	**Range**	**Min**	**Max**	**Range**
Beetroot	104	213	109	101	222	121
Bitter Cassava	102	213	111	112	189	78
Cabbage	137	269	132	102	191	89
Carrot	102	269	167	112	222	110
Cauliflower	102	213	111	112	222	110
Coco	119	269	150	104	222	118
Cow Peas	102	213	111	112	269	158
Cucumber	102	222	120	112	222	110
Dasheen	102	213	111	112	222	110
Egg Plants	104	222	118	112	269	158
Escallion	104	191	87	112	222	110
Gungo Peas	102	222	120	101	189	89
Horse	104	269	165	101	222	121
Lucea	102	213	111	112	222	110
Negro	102	222	120	112	222	110
Okra	101	222	121	112	269	158
Onion	104	222	118	101	213	112
Ordinary Corn	122	222	100	101	222	121
Other Lettuce	101	191	90	112	222	110
Peanut	101	213	112	102	222	120
Pineapple	102	213	111	101	222	121
Pumpkin	102	269	167	101	222	121
Red Peas	122	269	147	101	191	90
String Bean	101	213	112	112	222	110
Sweet Cassava	102	269	167	112	189	78
Tomato	104	269	165	112	222	110
Turnip	101	213	112	104	222	118
Watermelon	102	222	120	104	222	118
Yams (Yellow)	119	213	93	101	189	89

	Late Season Rainfall (mm)					
	Most Productive			Least Productive		
	Min	**Max**	**Range**	**Min**	**Max**	**Range**
Beetroot	130	232	102	139	233	94
Bitter Cassava	145	227	82	141	242	101
Cabbage	145	240	95	141	242	101
Carrot	145	240	95	139	242	103
Cauliflower	130	227	97	141	242	101
Coco	145	240	95	139	242	103
Cow Peas	130	242	112	139	240	101
Cucumber	139	227	88	141	242	101
Dasheen	158	240	82	141	242	101
Egg Plants	145	242	97	130	240	110
Escallion	145	240	95	130	218	89
Gungo Peas	139	232	93	145	242	97
Horse	130	240	110	141	242	101
Lucea	158	232	74	139	242	103
Negro	102	222	120	112	222	110
Okra	145	242	97	130	240	110
Onion	130	232	102	145	242	97
Ordinary Corn	130	240	110	139	218	80
Other Lettuce	145	242	97	139	218	80
Peanut	145	242	97	139	218	80
Pineapple	146	232	86	130	242	112
Pumpkin	158	240	82	141	242	101
Red Peas	130	240	110	141	242	101
String Bean	158	242	84	139	218	80
Sweet Cassava	130	240	110	141	233	92
Tomato	145	240	95	130	242	112
Turnip	145	242	97	139	218	80
Watermelon	130	232	102	146	242	96
Yams (Yellow)	130	227	97	141	242	101

APPENDIX B: SUITABILITY RULES FOR ANNUAL, EARLY and LATE SEASON RAINFALL FOR JAMAICA

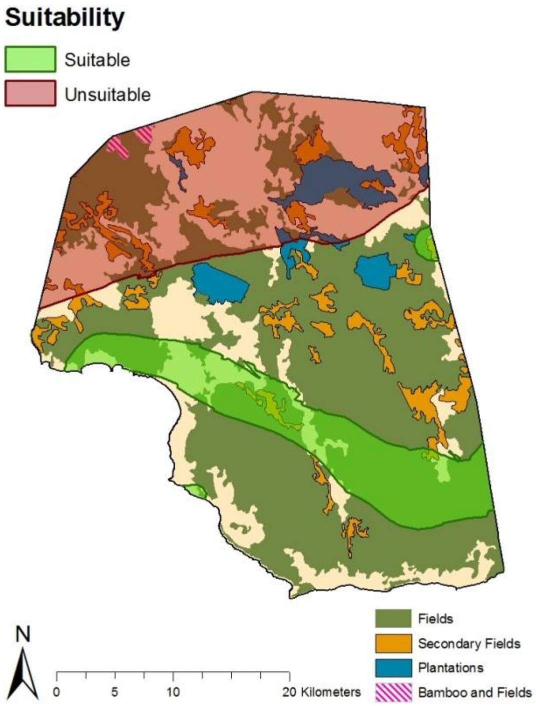
Crop Type	Annual Rainfall (mm) Suitability Rules
Beetroot	106 to 122 Suitable , > 162 Unsuitable
Bitter Cassava	< 122 Unsuitable, > 162 Unsuitable
Cabbage	< 127 Unsuitable, 158 to 198 Suitable
Carrot	< 127 Unsuitable, 162 to 198 Suitable
Cauliflower	106 to 113 Suitable , > 154 Unsuitable
Coco	< 122 Unsuitable, 168 to 198 Suitable
Cow Peas	< 106 Unsuitable, 162 to 173 Suitable
Cucumber	< 122 Unsuitable, > 162 Unsuitable
Dasheen	< 122 Unsuitable, > 162 Unsuitable
Egg Plants	< 122 Unsuitable, 168 to 173 Suitable
Escallion	< 127 Unsuitable, 173 to 198 Suitable
Gungo Peas	< 122 Unsuitable, > 168 Unsuitable
Horse	106 to 122 Suitable , 162 to 198 Suitable
Lucea	< 122 Unsuitable, > 154 Unsuitable
Negro	106 to 113 Suitable , > 168 Unsuitable
Okra	113 to 122 Suitable , 162 to 173 Suitable
Onion	< 106 Unsuitable, > 168 Unsuitable
Ordinary Corn	106 to 122 Suitable , > 168 Unsuitable
Other Lettuce	< 113 Unsuitable, > 173 Unsuitable
Peanut	< 113 Unsuitable, > 173 Unsuitable
Pineapple	122 to 122 Suitable , > 158 Unsuitable
Pumpkin	< 122 Unsuitable, 158 to 198 Suitable
Red Peas	106 to 122 Suitable , 162 to 198 Suitable
String Bean	< 113 Unsuitable, > 173 Unsuitable
Sweet Cassava	106 to 113 Suitable , 168 to 198 Suitable
Tomato	< 133 Unsuitable, 173 to 198 Suitable
Turnip	< 113 Unsuitable, > 173 Unsuitable
Watermelon	< 106 Unsuitable, > 168 Unsuitable
Yams (Yellow)	106 to 113 Suitable , > 154 Unsuitable

Crop Type	Early Season Rainfall (mm) Suitability Rules
Beetroot	< 104 Unsuitable, > 213 Unsuitable
Bitter Cassava	102 to 112 Suitable , 189 to 213 Suitable
Cabbage	< 137 Unsuitable, 191 to 269 Suitable
Carrot	102 to 112 Suitable , 222 to 269 Suitable
Cauliflower	102 to 112 Suitable , > 213 Unsuitable
Coco	< 119 Unsuitable, 222 to 269 Suitable
Cow Peas	102 to 112 Suitable , > 213 Unsuitable
Cucumber	102 to 112 Suitable , 222 to 222 Suitable
Dasheen	102 to 112 Suitable , > 213 Unsuitable
Egg Plants	104 to 112 Suitable , > 222 Unsuitable
Escallion	104 to 112 Suitable , > 191 Unsuitable
Gungo Peas	< 102 Unsuitable, 189 to 222 Suitable
Horse	< 104 Unsuitable, 222 to 269 Suitable
Lucea	102 to 112 Suitable , > 213 Unsuitable
Negro	102 to 112 Suitable , > 222 Unsuitable
Okra	101 to 112 Suitable , > 222 Unsuitable
Onion	< 104 Unsuitable, 213 to 222 Suitable
Ordinary Corn	< 122 Unsuitable, > 222 Unsuitable
Other Lettuce	101 to 112 Suitable , > 191 Unsuitable
Peanut	101 to 102 Suitable , > 213 Unsuitable
Pineapple	< 102 Unsuitable, > 213 Unsuitable
Pumpkin	< 102 Unsuitable, 222 to 269 Suitable
Red Peas	< 122 Unsuitable, 191 to 269 Suitable
String Bean	101 to 112 Suitable , > 213 Unsuitable
Sweet Cassava	102 to 112 Suitable , 189 to 269 Suitable
Tomato	104 to 112 Suitable , 222 to 269 Suitable
Turnip	101 to 104 Suitable , > 213 Unsuitable
Watermelon	102 to 104 Suitable , > 222 Unsuitable
Yams (Yellow)	< 119 Unsuitable, 189 to 213 Suitable

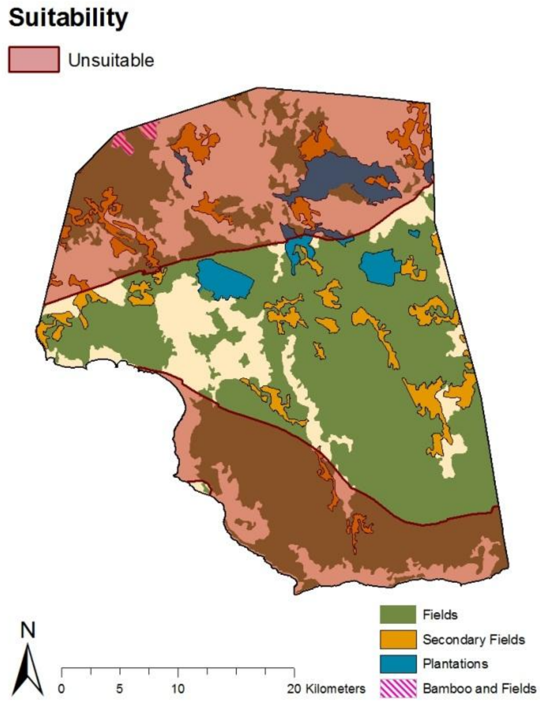
Crop Type	Late Season Rainfall (mm) Suitability Rules
Beetroot	130 to 139 Suitable , > 232 Unsuitable
Bitter Cassava	< 145 Unsuitable, > 227 Unsuitable
Cabbage	< 145 Unsuitable, > 240 Unsuitable
Carrot	< 145 Unsuitable, > 240 Unsuitable
Cauliflower	130 to 141 Suitable , > 227 Unsuitable
Coco	< 145 Unsuitable, > 240 Unsuitable
Cow Peas	130 to 139 Suitable , 240 to 242 Suitable
Cucumber	139 to 141 Suitable , > 227 Unsuitable
Dasheen	< 158 Unsuitable, > 240 Unsuitable
Egg Plants	< 145 Unsuitable, 240 to 242 Suitable
Escallion	< 145 Unsuitable, 218 to 240 Suitable
Gungo Peas	139 to 145 Suitable , > 232 Unsuitable
Horse	130 to 141 Suitable , > 240 Unsuitable
Lucea	< 158 Unsuitable, > 232 Unsuitable
Negro	102 to 112 Suitable , > 222 Unsuitable
Okra	< 145 Unsuitable, 240 to 242 Suitable
Onion	130 to 145 Suitable , > 232 Unsuitable
Ordinary Corn	130 to 139 Suitable , 218 to 240 Suitable
Other Lettuce	< 145 Unsuitable, 218 to 242 Suitable
Peanut	< 145 Unsuitable, 218 to 242 Suitable
Pineapple	< 146 Unsuitable, > 232 Unsuitable
Pumpkin	< 158 Unsuitable, > 240 Unsuitable
Red Peas	130 to 141 Suitable , > 240 Unsuitable
String Bean	< 158 Unsuitable, 218 to 242 Suitable
Sweet Cassava	130 to 141 Suitable , 233 to 240 Suitable
Tomato	< 145 Unsuitable, > 240 Unsuitable
Turnip	< 145 Unsuitable, 218 to 242 Suitable
Watermelon	130 to 146 Suitable , > 232 Unsuitable
Yams (Yellow)	130 to 141 Suitable , > 227 Unsuitable

APPENDIX C: SUITABILITY MAPS FOR ANNUAL RAINFALL

Ordinary Corn

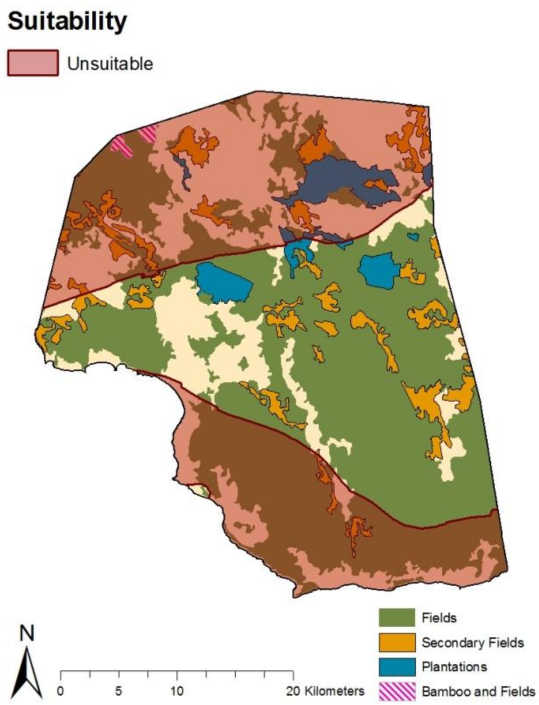


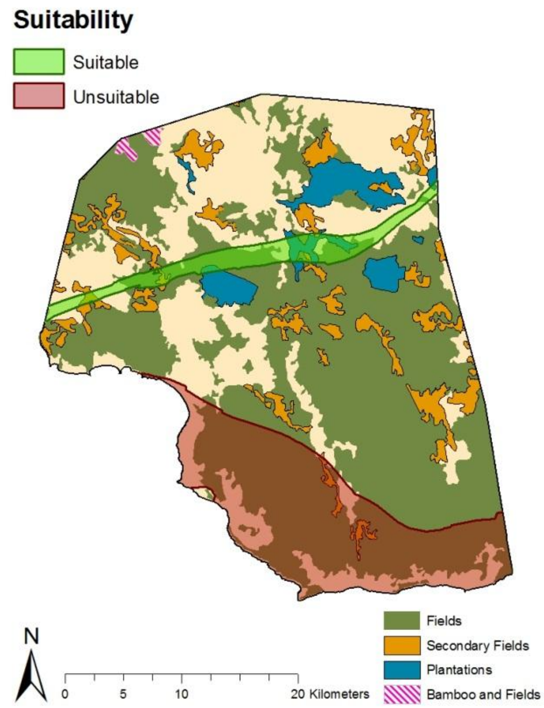
Onion



Watermelon

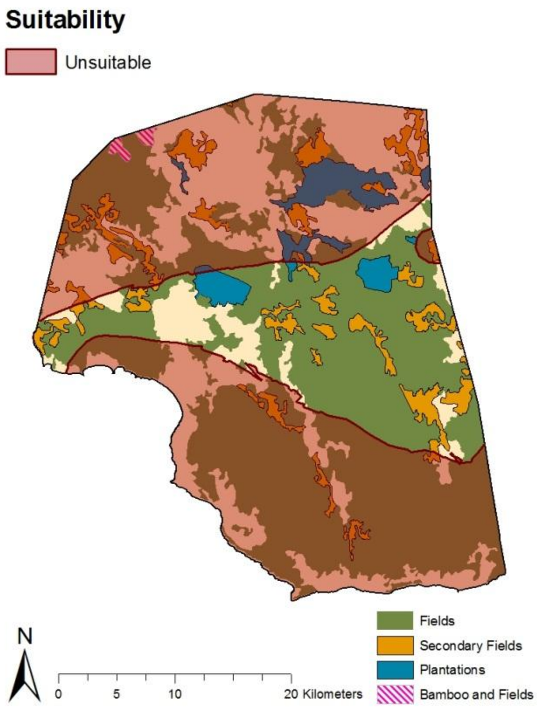
Cow Peas

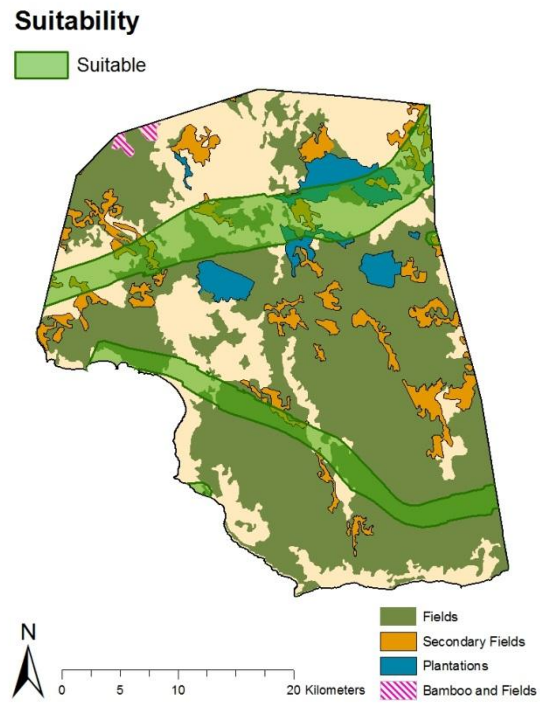

Suitability
Unsuitable
N
0
5
10
20 Kilometers
Fields
Secondary Fields
Plantations
Bamboo and Fields


Suitability
Suitable
Unsuitable
N
0
5
10
20 Kilometers
Fields
Secondary Fields
Plantations
Bamboo and Fields

Bitter Cassava

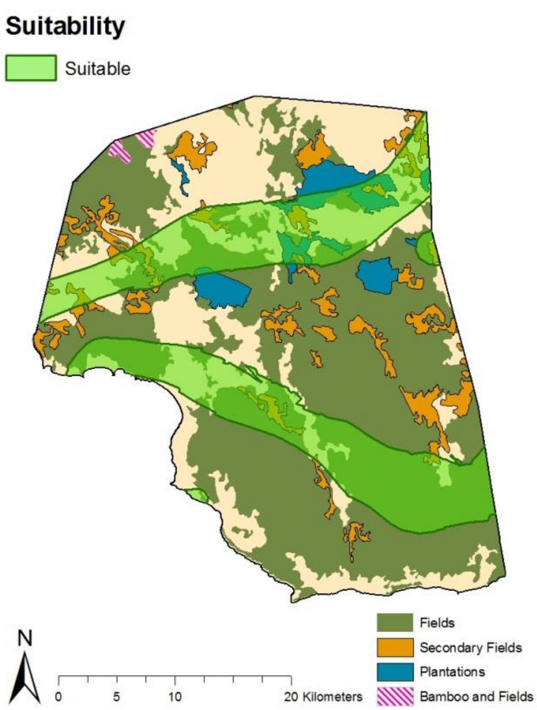
Sweet Cassava

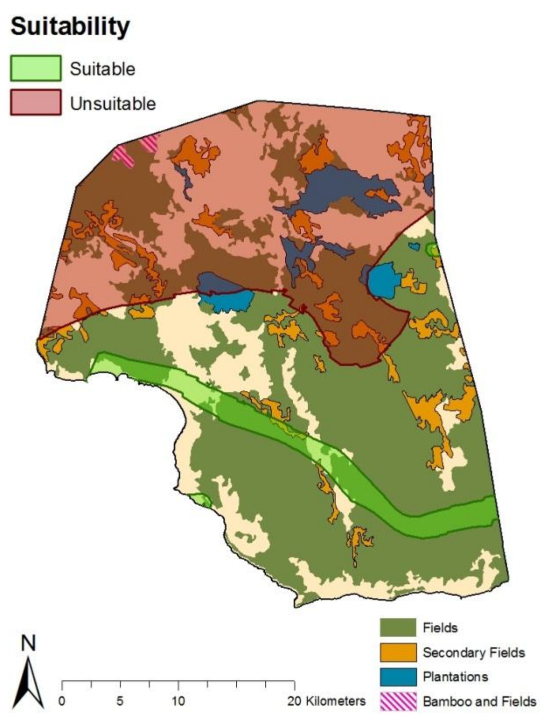




Horse

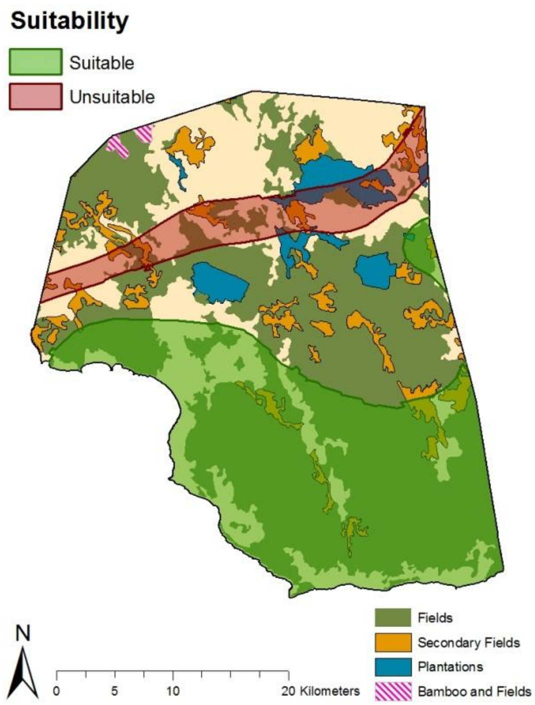
Cauliflower

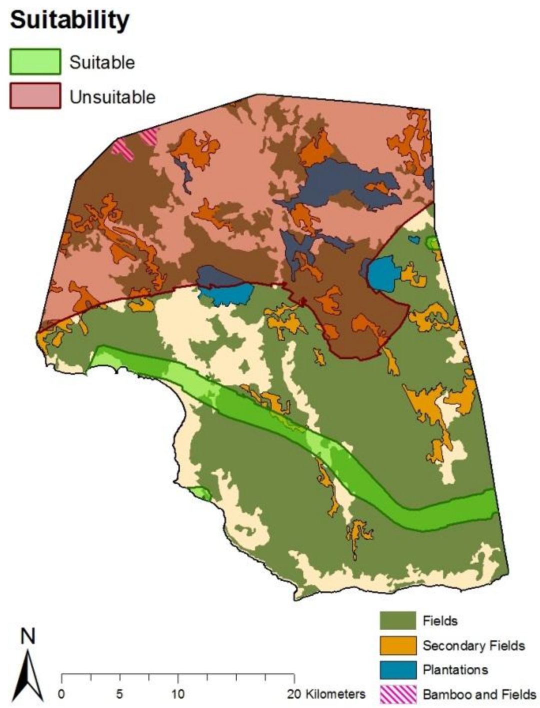




Tomato

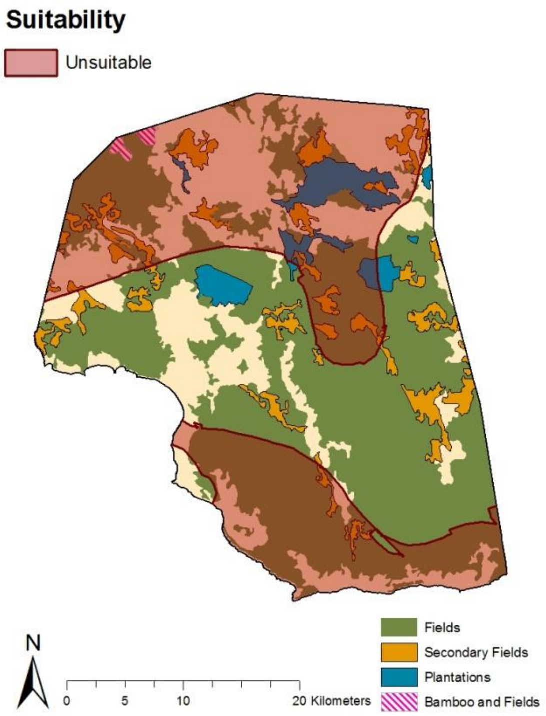
Yams


Suitability
Suitable
Unsuitable
N
0
5
10
20 Kilometers
Fields
Secondary Fields
Plantations
Bamboo and Fields

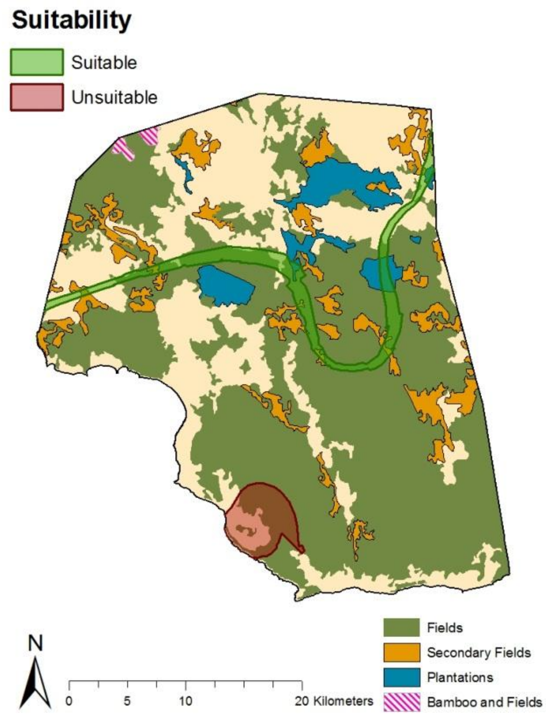

Suitability
Suitable
Unsuitable
N
0
5
10
20 Kilometers
Fields
Secondary Fields
Plantations
Bamboo and Fields

APPENDIX D: SUITABILITY MAPS FOR EARLY SEASON RAINFALL

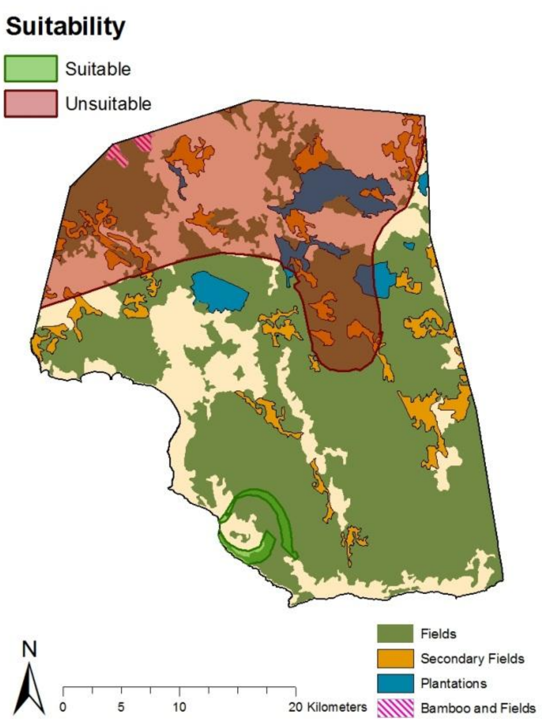
Ordinary Corn



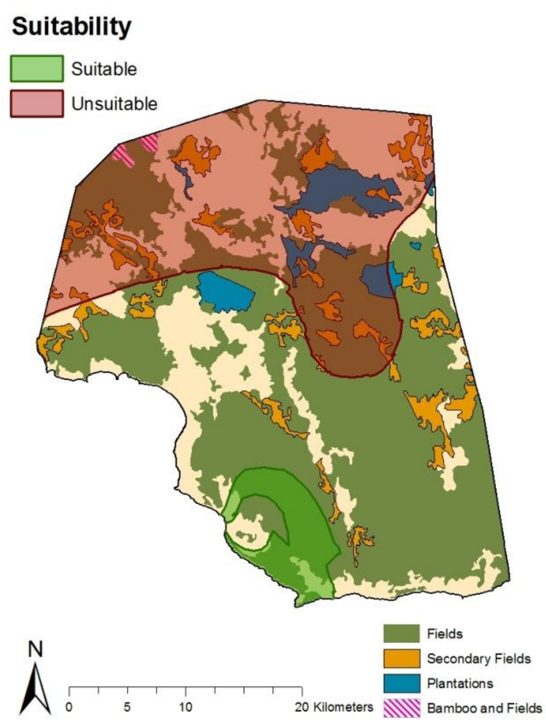
Onion



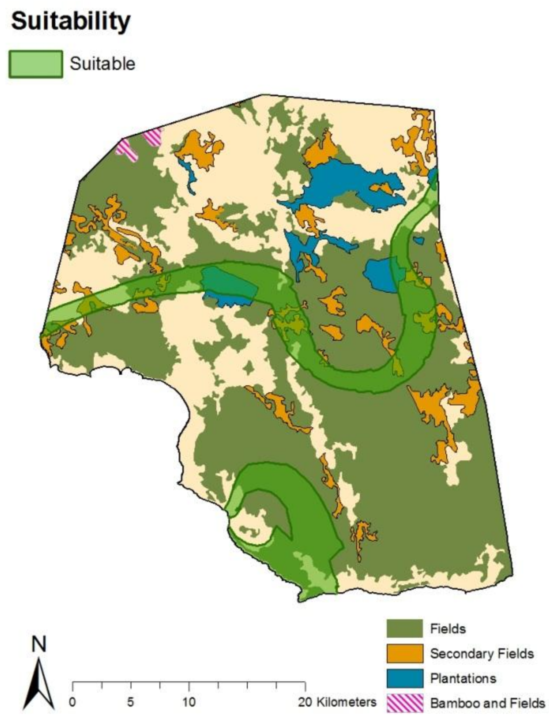
Watermelon



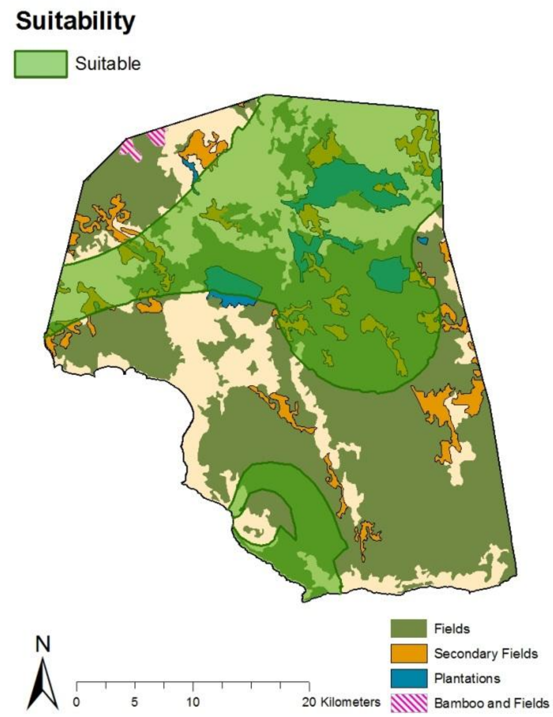
Cow Peas



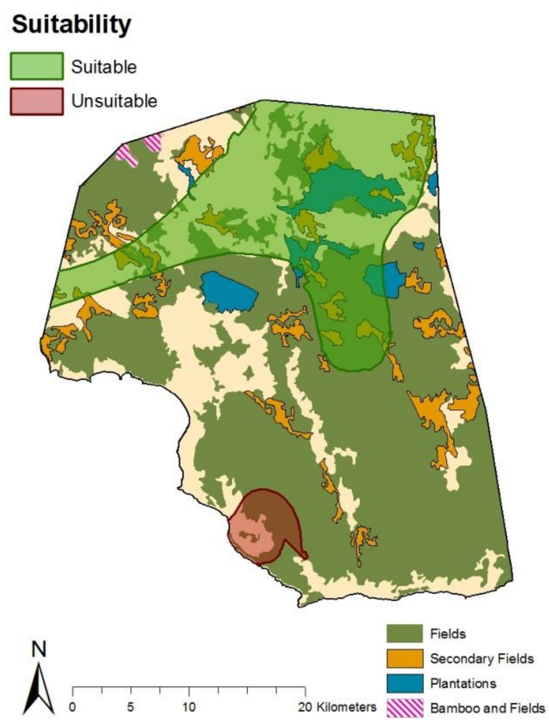
Bitter Cassava



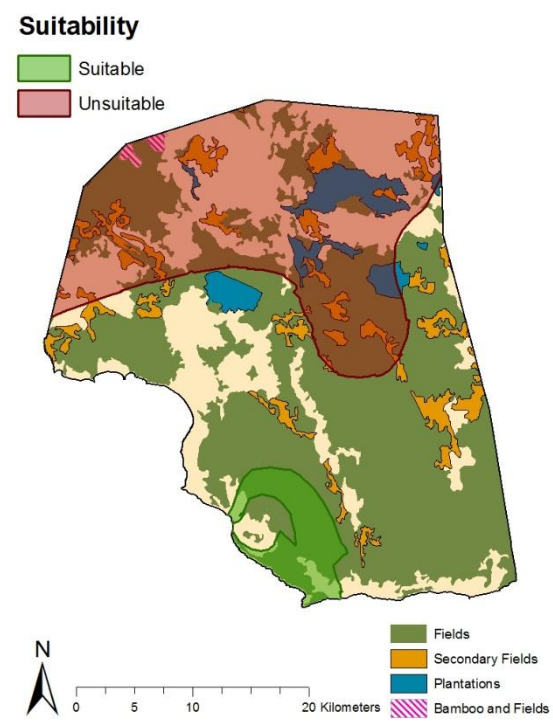
Sweet Cassava



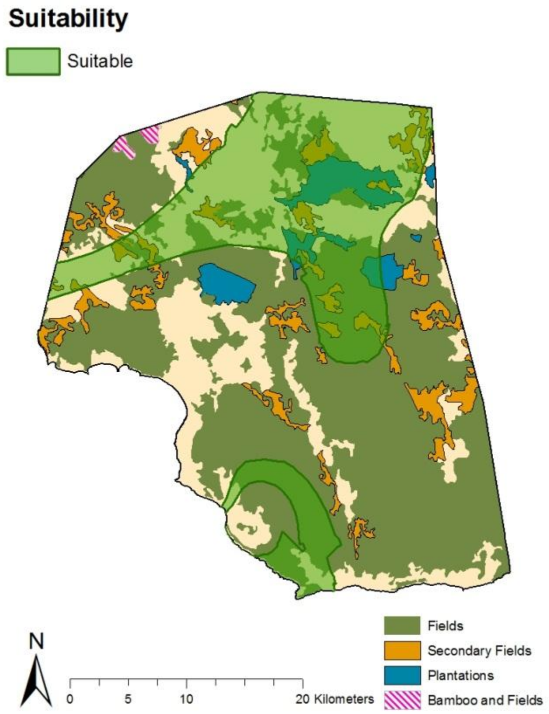
Horse



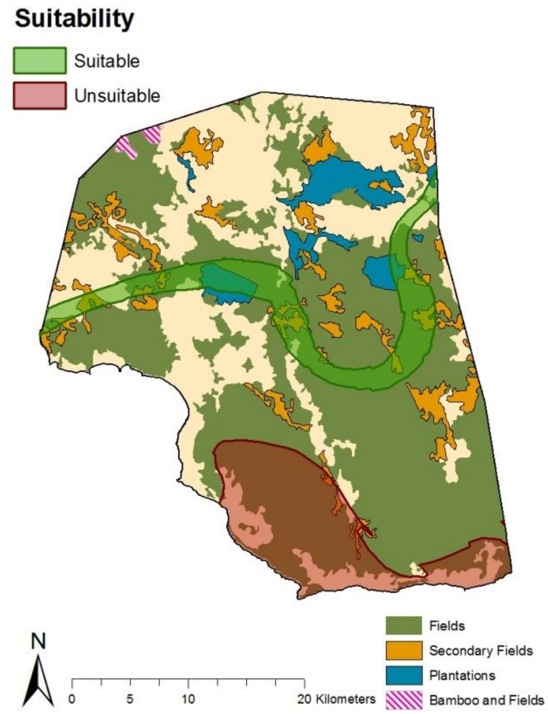
Cauliflower



Tomato

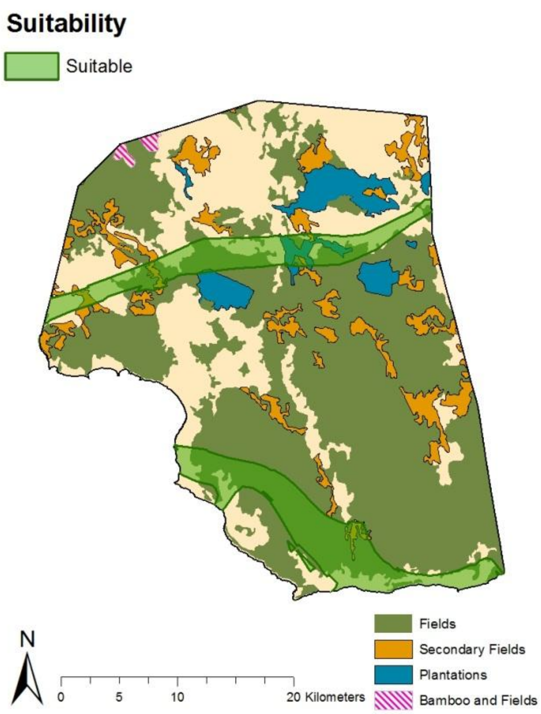

Suitability
Suitable
Fields
Secondary Fields
Plantations
Bamboo and Fields
N
0
5
10
20 Kilometers

Yams

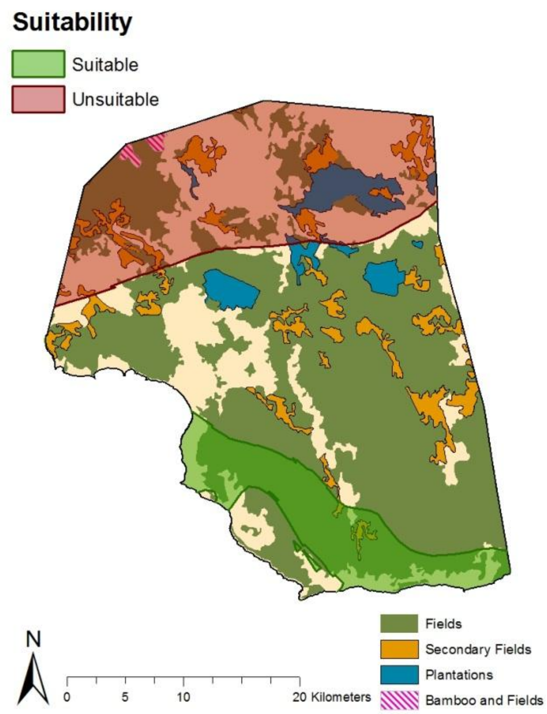

Suitability
Suitable
Unsuitable
Fields
Secondary Fields
Plantations
Bamboo and Fields
N
0
5
10
20 Kilometers

APPENDIX E: SUITABILITY MAPS FOR LATE SEASON RAINFALL

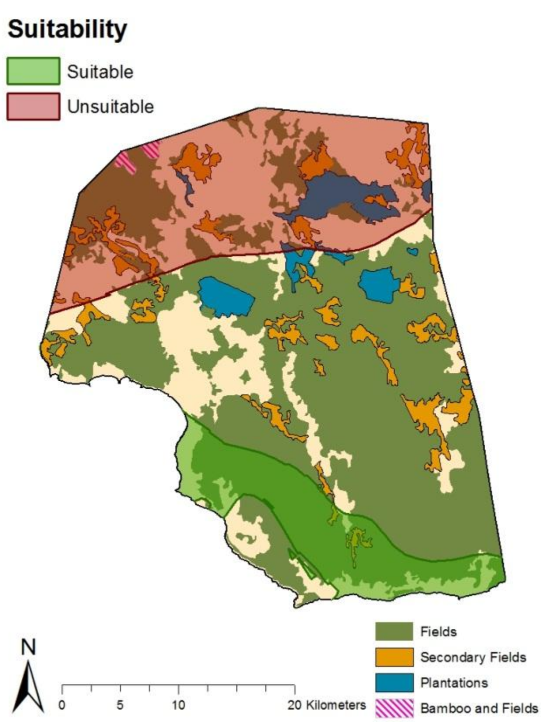
Ordinary Corn



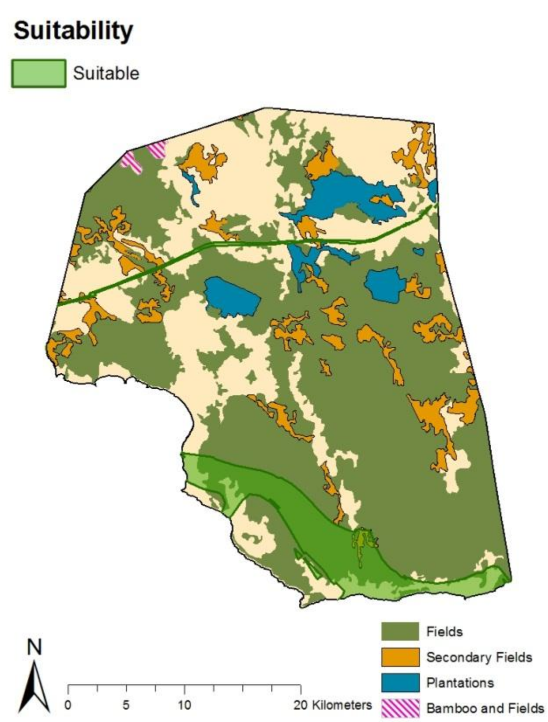
Onion



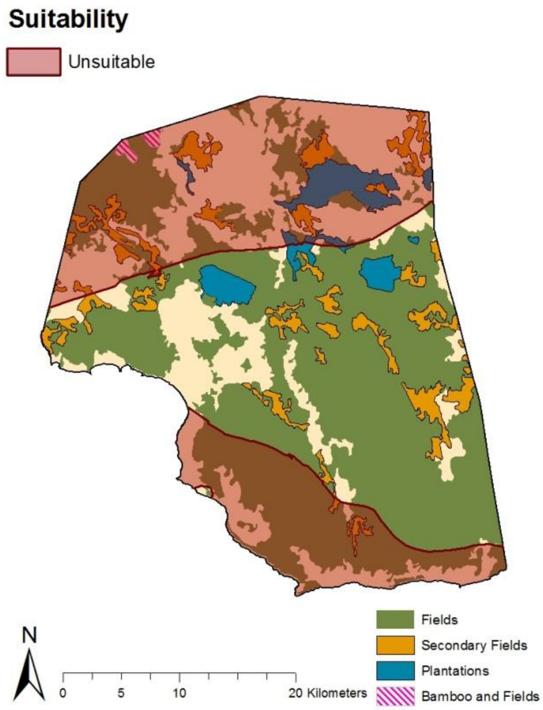
Watermelon



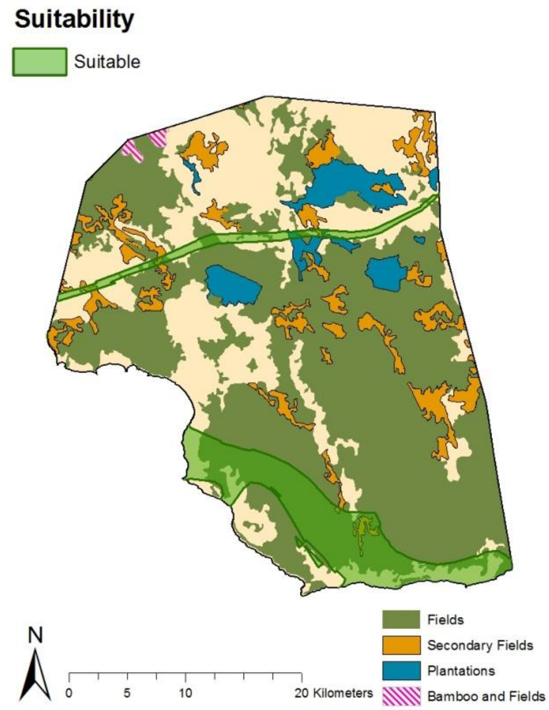
Cow Peas



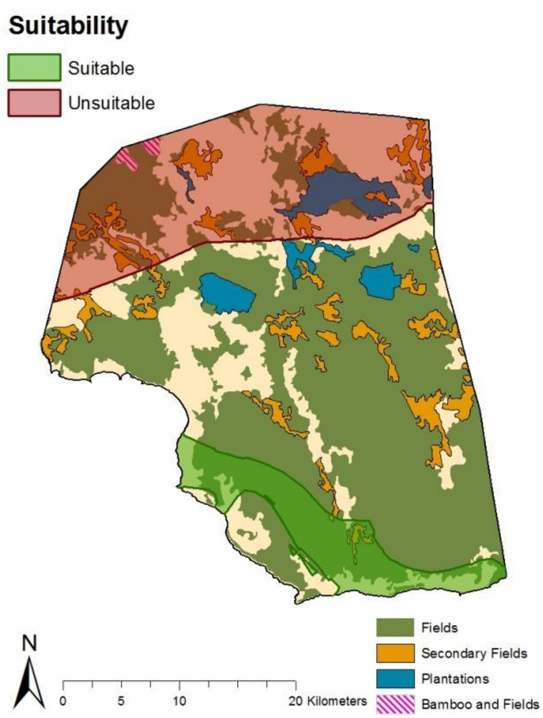
Bitter Cassava



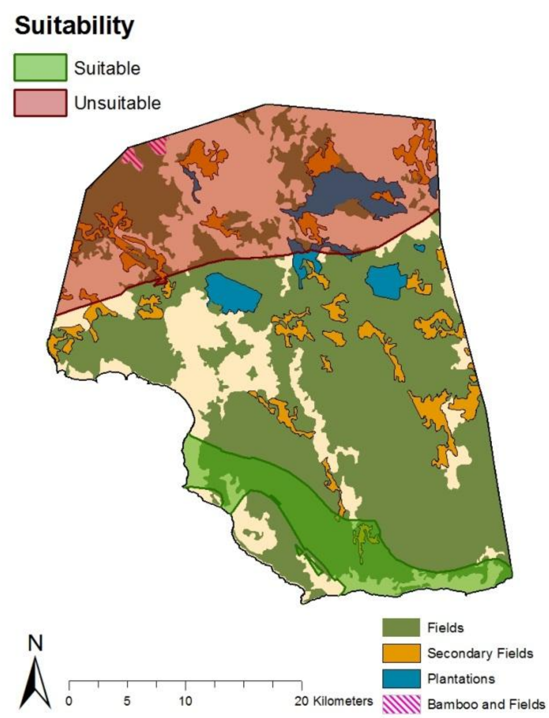
Sweet Cassava



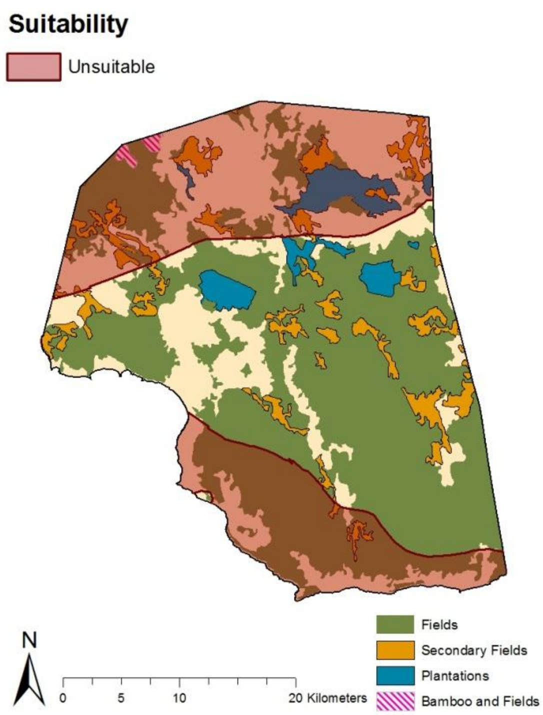
Horse



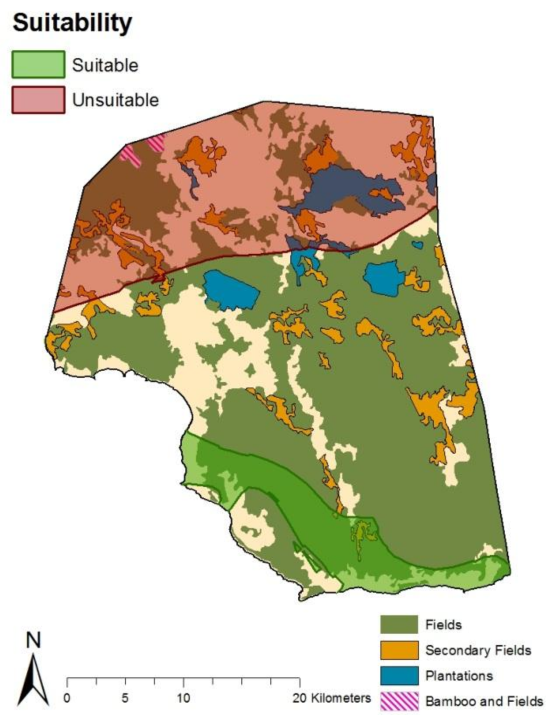
Cauliflower



Tomato


Suitability
Unsuitable
N
0
5
10
20 Kilometers
Fields
Secondary Fields
Plantations
Bamboo and Fields

Yams


Suitability
Suitable
Unsuitable
N
0
5
10
20 Kilometers
Fields
Secondary Fields
Plantations
Bamboo and Fields