Land-Use Changes in Southwestern Guatemala: Assessment of their Effects and Sustainability

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Abstract

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Land-use changes in the Pacific coastal plain of southwest Guatemala have accelerated in the past twenty years as native arable and pasture lands have been converted at an increasing rate to oil palm and banana plantations. This study of the changes during this period has been made by remote-sensing analyses calibrated to field observations and water analyses. It has been determined that the changes, which include soil erosion, measureable contamination of streams by sediment and chemicals, and deterioration of lands adjoining plantations, have a long-range detrimental (non-sustainable) effect in terms of the ecosystem. As an example of the effects on adjoining lands, there is excess of water on them during the wet season, when the plantations use drainage procedures, and water shortages during the dry season, when the plantations use much of the available water for irrigation.

These empirical observations of land degradation and productivity deterioration outside the plantations accompanying the introduction and expansion of the plantations are confirmed and substantiated by statistical treatment of remotely sensed data. In particular, vegetative cover, as measured by the Normalized Difference Vegetation Index (NDVI), indicates statistically significant differences during the period of plantation activity. This finding is supported by the results of permutation tests and variability trend analysis, which are well suited for testing non-parametric data, a characteristic of the data of this study area. Water quality, especially values of chloride, arsenic, nitrites, and nitrates, is also of concern, when compared with international standards.

The results of this study should aid in decision-making of the Guatemala governing bodies as they decide what practices are in the best interests of the people – practices that are sustainable. Also, this study shows that surface-calibrated remote-sensing methods allow assessment of land-use changes in areas that otherwise would be without assessments because of budgetary restrictions.

This study also includes compilation/synthesis of background information in terms of meaningful parameters of sustainability and the physical setting, as they pertain to Guatemala. Correspondingly, the first parts of the dissertation focus on generalizations of sustainability and land-use changes and the geology, soils, and hydrology of the region.

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I gratefully acknowledge my co-chair members, Dr. Kristiina Ann Vogt and Dr. Dan Vogt, who provided guidance, expertise and encouragement with my research and provided me with many learning opportunities. Also, from my committee members: Dr. Miles Logsdon – your assistance with research design and remote sensing was invaluable, and Calvin Mukumoto – your friendly and expert advice was always appreciated. I am indebted to Dr. Frank Roberts, who came in at the last minute to be my GSR when Dr. Godoy went on maternity leave. I am grateful to Dr. Loveday Conquest, who was invaluable in providing statistics advice, hired me twice to be her statistics teaching assistant, and acted as a terrific mentor. A special thanks to School of the Environment staff Amanda Davis, Marc Morrison, and Michelle Trudeau who went out of their way more than once to help me. Throughout my studies I was fortunate to be part of the NSF Bioenergy IGERT, guided by Dr. Daniel Schwartz and Dr. Laurie Stephan, and the Program on Climate Change, directed by Dr. LuAnne Thompson and Dr. Miriam Bertram. This research could not have happened without the Center for Human Rights Research Group, led by Dr. Angelina Godoy and supported by Wolfgang Krenmayr of the Archdiocese of San Marcos in Guatemala, and UW graduate students Ken Faires, Kurt Spies, and Geoffrey Morgan. Additional recognition must be credited to my lab mates, Dr. Lloyd Nackley, Stephan Gmur, Jason Scullion, Lauren Grande, and Maria Sandercock. A huge thank you to my friends for their support along this journey – Merle, Diane, Jill, Angie, Laurie and Maria. Also, a thank you goes to my IGERT friends Azra Vajzovicv and Jenny Knoth. I also want to thank Dr. Darlene Zabowski and Dr. Susan Bolton for their helpful advice.

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Introduction and Dissertation Road Map

Since the early 2000s, large monocropping plantations of bananas and African Palm have been making major alterations to the ecosystem in southwestern Guatemala by removing wetlands, rerouting the river, altering the river banks, and building dams, in addition to introducing chemical changes from pesticides and fertilizer. These land-use and land-cover changes appear to have resulted in significant changes in ecological functions, such as erosion control, nutrient cycling, water quality, loss of biodiversity, and climate regulation. It is suspected that the pressure of these changes has pushed these lands beyond sustainable thresholds, given the current low soil productive capacity of the subsistence agriculture in this region. The purpose of this research is to explore and explain these patterns of land-use change and their impacts on the total productive capacity of landscapes in nutrient-depleted soils.

Location and General Description of Study Area

The study area lies in the Pacific coastal alluvial plain of Guatemala (Figure I.1). Short rivers drain the highlands across the coastal plain, ending in a biotically productive lagoon and mangrove estuary zone. Replenishment of soil nutrients on the coastal plain by air-fall volcanic ash and water-borne sediments contributes to high agricultural productivity. However, as noted above, changes in land-use in the last decade, in particular, now present a potential crisis in the ecosystem of the area, especially in agriculture, on which the residents depend so heavily. For example, estimates derived from Landsat satellite imagery for the time period from 1998 to 2011, during the dry season, show that the banana plantations in the study area have increased from approximately 660 square kilometers to 940 square kilometers. Palm plantations have increased from 210 square kilometers to 1,602 square kilometers (see Figure 3.3). A rather detailed description of these factors is presented in chapters 2 through 4.

Figure I.1. Generalized topographic map of Guatemala, with study area location in northwestern part of the country (adapted from Google.com//imgres?g=Guatemala+topographic+map).

Research Design

The above-stated purpose of this research in more specific terms is to detect and explain the changes in land-use/land-cover dynamics for an area in Guatemala over the past ten years. The methodology used will allow identification of “hotspot” areas for potential restoration in order to improve ecosystem services that have been lost. There are two types of land-cover changes and/or conversions occurring: 1) less intensive agriculture, less reliant on fertilizer and irrigation, and 2) wetlands to intensive agriculture (palm and banana plantations). Due to the remoteness of the subject area, there is very little field data presently available to explain the environmental changes that are of concern to local inhabitants.

Given the absence of historical field data in Guatemala, particularly in the study area, there has been a heavy reliance on satellite imagery to reconstruct the land-use changes over time. The availability of remotely sensed data for this site allows the study of locations and scales not possible using field-intensive methods. The classification of the landscape into land-cover classes allows a quantification of trends in land-cover change over time. (Lambin and Giest 2006, Ustin 2004, Cohen and Goward 2004). The use of remote sensing and Geographic Information Systems (GIS) permits monitoring and spatial analysis of land-use/land-cover change. Change-detection methods utilizing remotely sensed images can be used to compare two or more dates of imagery to identify the type of change and the quantified amount of change. A time-series analysis of seasonal Normalized Difference Vegetation Index (NDVI) is a method to estimate productivity over time (Jones and Vaughan 2006, Jensen 1996). Discrete methods of classification have predominantly been used to derive and analyze land-cover change. The problem with these methods is that modifications can be as significant as land-cover conversions, resulting in a land-cover class change, but because the classification would not change, these changes and modifications would not be obvious (Foody 2002, Lambin 1999, Southworth et al. 2004).

Research Questions

- How does the conversion of land to palm and banana plantations affect the productivity and variability in productivity in the surrounding landscape over time?
- Are there noticeable changes or patterns in water quality parameters, either adjacent to the plantations or downstream?

Hypotheses

- The conversion of land to palm and banana plantations (less intensive agriculture to intensive) increases the productivity of the plantation lands and decreases the productivity of adjacent lands.
- The conversion of land to palm and banana plantations (less intensive agriculture to intensive) decreases the variability in productivity of the plantation lands and increases the variability in productivity of adjacent lands.

Dissertation Road Map

This dissertation consists of four main parts, each of which represents an important aspect of the problems addressed in it. Firstly, the underlying concept/philosophy is sustainability, which is the key to appraising the conditions and practices in the study area, the southwestern part of Guatemala that adjoins the Pacific Ocean. Chapter 1 summarizes the concept of sustainability of land-use based on the principles and methods presented in the work of Vogt et al. (2010a) and presents country-wide parameters, described by Vogt et al. (2010a), which are reasonable measurements of sustainability. These parameters include Human Development Index (HDI), population density, types of energy sources and their use, types of land-cover, and water footprint.

Chapter 2 presents a physical setting for the country and the study site. Historical and current land-use is augmented with the geologic framework (including hazards), soils, and hydrology. These three provide the setting and conditions for human existence without the consideration of social and political circumstances.

Remote sensing methods, using temporal sets of data, provide the data for the assessment of land-use change and conversion, and is the topic of Chapter 3. The methodology is presented as well as the conclusions, in particular, land-use, its changes, and their effects over a twenty-year period.

Water-quality and its areal changes during four different field sampling trips are analyzed in Chapter 4. Conclusions and recommendations for future studies are presented in Chapter 5. The area for study should be expanded, as should field studies, with calibration to remote sensing so that accuracy of the latter, on its own, will be improved and assessment of larger areas can be made with a high confidence level.

Chapter 1: Motivations for Studying Landscape Change

Landscape Change and Sustainability in Use of Earth‘s Resources

In the 21st century, sustainability, as described and expounded in *Sustainability Unpacked* by Vogt et al. (2010a), is the key not just for human survival but for continued improvement of life for them. Sustainability is the underlying ideal of this research inasmuch as conversion of land-use must result in a net betterment of the people and their surroundings. Sustainability is discussed herein in regard to energy, water, food, forest materials, soils, and the major roles they have in constraining or enhancing sustainability choices because of their impacts on environmental and social resilience. The most important factor in regard to sustainable use of the earth's resources is population, but an in-depth study of it is beyond the scope of this work. Water, along with energy, especially in the form of green or renewable energy supplies, is one of the major drivers of landscape changes. Water, a focus of the local aspect of this study, summarizes how energy functions as a driver of landscape changes in industrialized, as well as in many developing, countries. These discussions are used to set the context for Guatemala, to understand the impacts of land-use changes, and to determine whether sustainable choices are being made that do not jeopardize the livelihood of local communities.

This study focuses on how a search for alternative and additional food supplies, with their requirements for water and energy, impact where land-use changes are implemented and why these changes are influencing the sustainability of their environments, especially water quality and food. Therefore, it is important to briefly examine how these are interconnected and why land-use changes are such a critical element of human landscapes. It is especially important to understand these connections since the demand to alter more land for the benefit of global societies continues to accelerate (Vogt et al. 2010a). How these changes decrease social and environmental resilience at the local level is less well known since the emphasis has been on global-level changes, such as climate change (e.g., Fagan 2008).

Much of the land-use changes occurring in the world are being driven by industrialized societies that are increasing their demands for green resource supplies that are found in rural parts of many developing countries (Vogt et al. 2010a; Setiono 2008). In other cases, the industrialized countries' demands stimulate business entrepreneurs in developing countries to build new business enterprises on lands that appear to be unoccupied but have local communities who have used these lands seasonally over centuries. This is the case in Guatemala and will be the focus of a later chapter in this dissertation. Because the local communities are dependent on the same lands for their survival, and where the soils and climatic conditions often are less able to support increased utilization or their conversion to another land-use, the lands' productive capacity and societies dependent upon them become more vulnerable to these changes (Vogt et al. 2010a).

A brief summary is provided of the links between resource extraction, land-use change, and deforestation as they are related to human well-being of communities living in rural areas. This review focuses on water, energy, food production, and forests because these are the factors mostly driving or being impacted by land-use changes in Guatemala. These reviews compare and contrast Guatemala to 34 other countries to index changes occurring in Guatemala and set a context for the drivers of change. The first discussion topic is the Human Development Index (HDI), which is critical to understand Guatemala's current position in this internationally developed evaluation tool. Since most countries that are lower in the HDI ranking want to move up in the ranking, understanding the social context for Guatemala will provide evidence for the factors that will constrain or create opportunities for Guatemala to improve its ranking. This is followed by a brief review of fossil and renewable energy use currently in Guatemala, as compared to 34 other countries. Next, the current land-uses and the distribution of land-cover are reviewed to identify whether Guatemala has the land-cover types to adopt alternative energy crops and whether land-use changes can be socially sustainable. Since forest-cover has been provided for the survival needs of rural Guatemala communities, the impacts of deforestation is briefly reviewed. Finally, the links between water and energy and food production are summarily reviewed inasmuch as this is especially relevant for the Guatemala context.

Human Development Index (HDI)

International communities have developed an index of human development that is a meaningful way to compare human or social capital of a country (Vogt et al. 2010a). It focuses on the potential of a country to develop based on its human characteristics. The HDI includes consideration of education levels, life expectancy, the role of women in a countries economy, along with consideration of health (HDI 2007/2008). It may be considered an overall measure of a country in terms of solar capital, solar income, and social or human capital. The HDI rank for the 34 countries studied by Vogt et al. (2010a) and Guatemala is shown in Figure 1.1. In HDI, Guatemala is ranked in the lowest 30% of the countries studied, suggesting that it faces serious economic development problems.

Guatemala needs to raise its HDI rank in the face of high poverty rates and a high dependence on natural-resource extraction for its income generation. As reported by the United States Central Intelligence Agency (CIA) (2012), Guatemala’s gross domestic product (GDP) per capita was estimated to be $5,000 in 2011. Guatemala is very dependent upon natural resources for its economic development even though most of the GDP by sector is in the services (62.7% in 2011) and agriculture (13.3% in 2011) (CIA 2012). Despite this low employment in agriculture, in 2011 38% of the labor force worked in agriculture and only 48% worked in the service sector (CIA

2012). Even though the 2011 unemployment rate was 4.1%, 54% of Guatemalans live below the poverty level. These data provide the context for Guatemala and the choices it has to make related to economic development in order to improve its HDI rank and development of its resource base.

The data for Guatemala (Figure 1.1) suggest that resource-use decisions should consider its high poverty rates as well as its high employment in the agricultural sector. These facts indicate that any land-use change has the potential to impact the employment activities and, thereby, have repercussions on Guatemala's HDI rank. Guatemala, with approximately 15 million people, has a larger population density than any other Central American country and most of the other tropical countries studied by Vogt et al. (2010a) (Figure 1.2). Also, it has restricted land areas (Figure 1.3) that can be used to produce food and ecosystem services from natural environments. This will further exacerbate the effects of land-uses changes that reduce land area delivering these services.

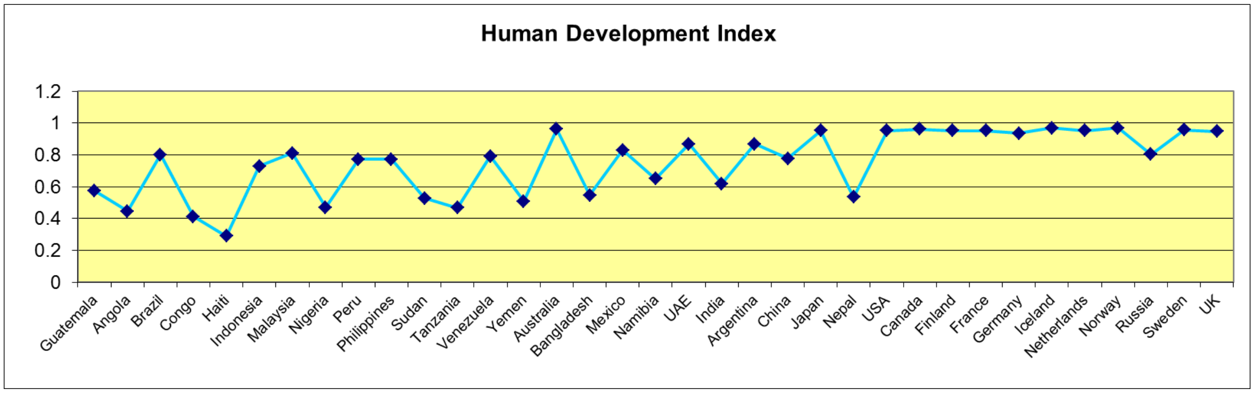


Figure 1.1. HDI for 35 countries: 34 for which country-level indices, or parameters, were categorized by Vogt et al. (2010a), and Guatemala.

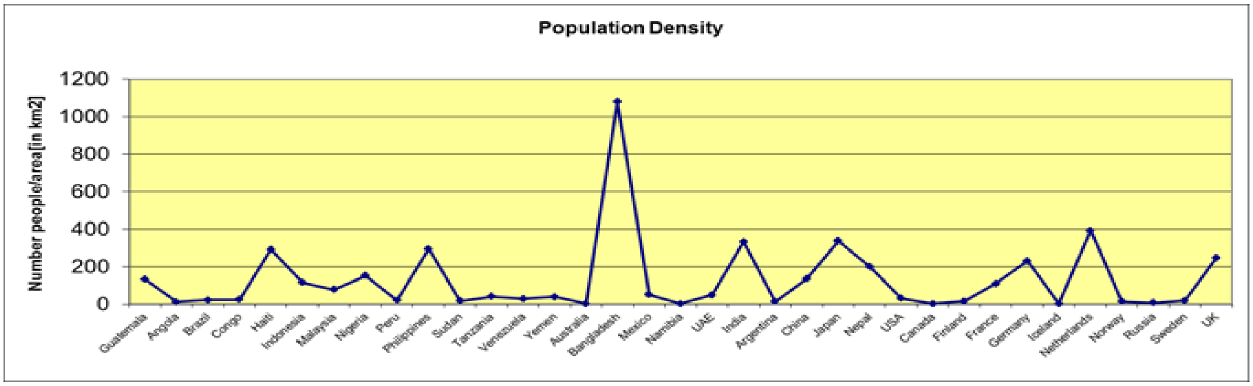


Figure 1.2. Population density (number of people/km^2) in the 34 countries studied by Vogt et al. (2010a) and Guatemala.

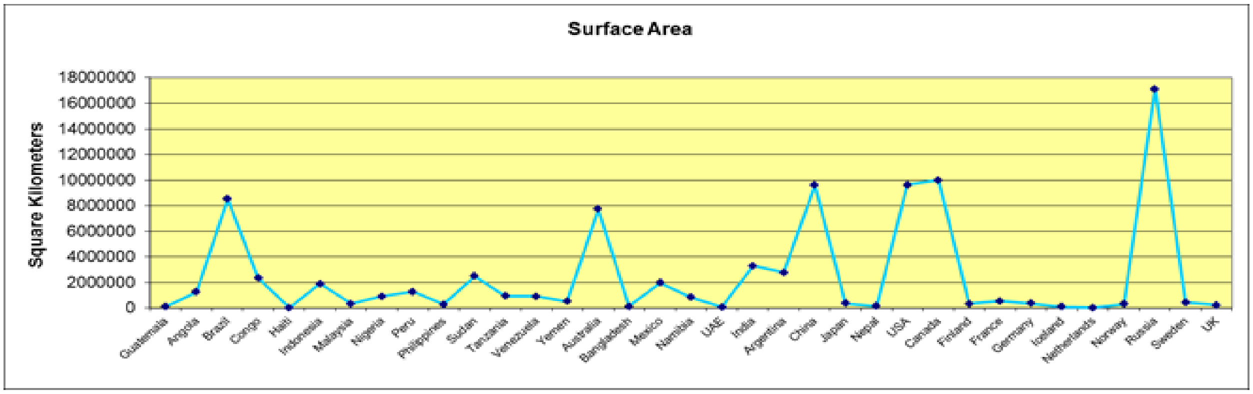


Figure 1.3. Surface areas of the 35 countries, including Guatemala; the other countries were studied by Vogt et al. (2010a).

Fossil and Renewable Energy

Fossil Energy

Because energy consumption is driving a considerable amount of the land conversion globally, it is important to understand how self-sufficient any country is in its energy supplies. Guatemala produces only about 13,000 barrels of oil per day (or 5 ounces per day per human) from the northern part of the country, whereas it consumes approximately 71,000 barrels per day (CIA 2012). Obviously high oil prices have an adverse effect on Guatemala and its HDI ranking. Yet is should be noted that the CIA (2012) estimates the reserves at 83 million barrels, and Clean Global

Energy of Australia has recently acquired an interest in two oil and gas development and exploration blocks in Guatemala (equities.com 2012). On a small scale, Guatemala is somewhat similar to countries in Africa where they own oil reserves, but the income is not being used to change the livelihood of rural communities (Vogt et al. 2010a).

When comparing Guatemala to the other 34 countries, Guatemala's fossil fuel energy use is at the lower end (Figure 1.4). This suggests that oil consumption may not be currently driving energy choices, nor is oil powering its economies to any significant level. It also suggests that natural resources are probably the dominant energy source in-country and that forests are an important source of local community energy.

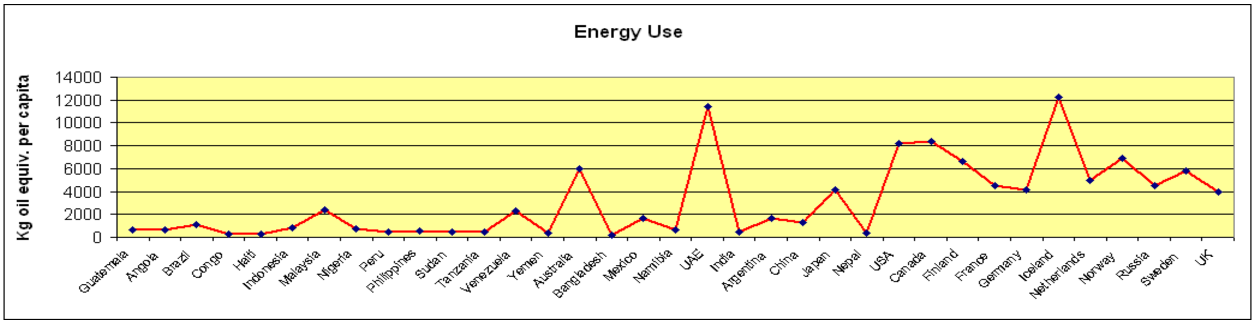


Figure 1.4. Energy use (kg oil equivalent per capita) in 35 countries, including Guatemala; country-level indices (parameters) were categorized by Vogt et al. (2010a).

Forests and Renewable Energy

The indices of energy use and amount derived from renewable sources are shown for 35 countries, including Guatemala, in Figures 1.5 and 1.6. The importance of forest biomass in providing for the energy needs of Guatemalan communities is shown in Figure 1.5. Almost 40% of Guatemala's energy is derived from forest materials while more than half of its energy consumed is based on renewable materials.

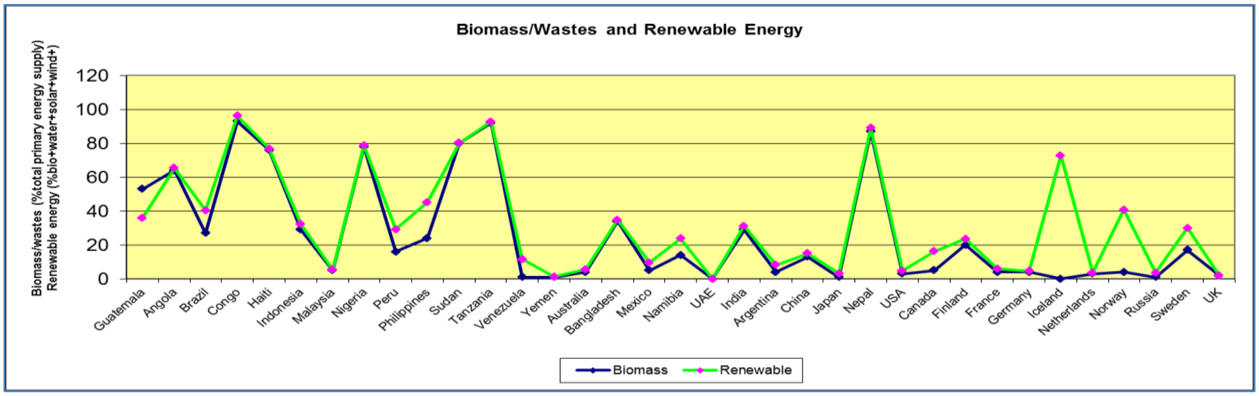


Figure 1.5. Biomass and wastes, as % total primary energy supply in 35 countries that include Guatemala; total renewable energy, as % total primary energy supply. The other 34 countries were studied by Vogt et al. (2010a).

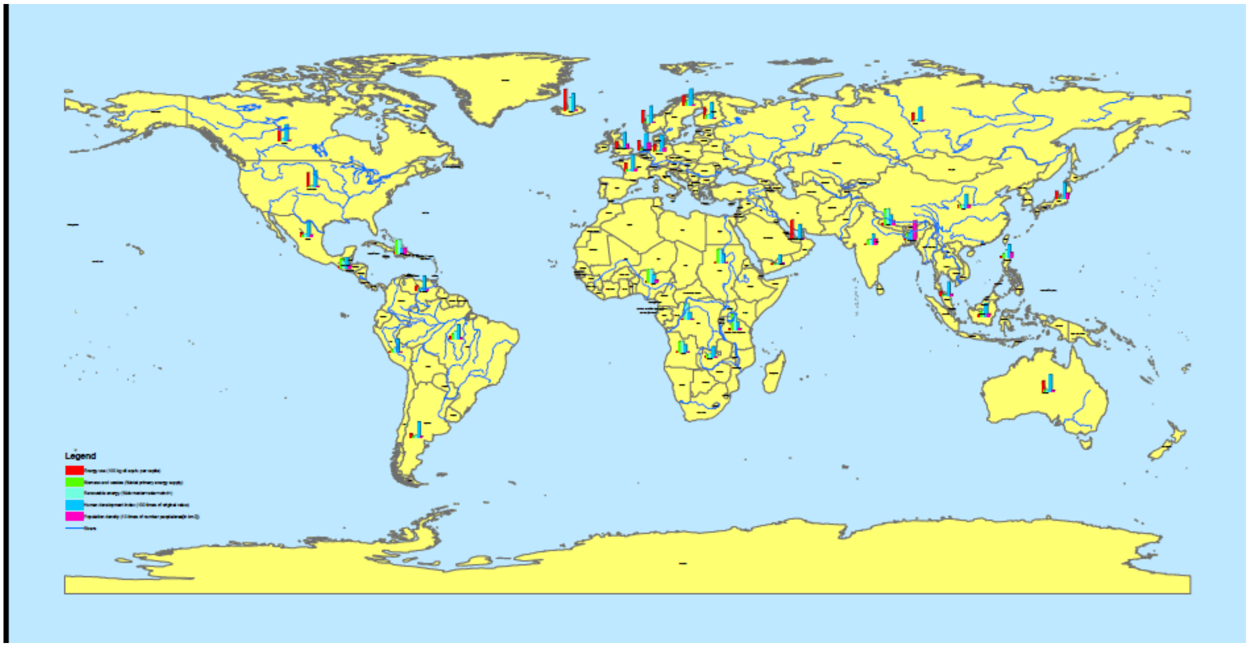


Figure 1.6. Map of relative energy use derived from biomass and wastes and renewable energy sources for the 34 countries studied by Vogt et al. (2010a) and Guatemala. It also includes relative HDI rank and the population density for each country.

Guatemala uses less forest materials or other renewable resources for energy production than countries such as the Democratic Republic of the Congo, Nepal, Nigeria, and Tanzania. Despite this statistic, the relative rate of consumption of forest materials is higher in Guatemala than these other countries. All these countries have been historically dependent on their forests for collecting fuel-wood for cooking and heating purposes but now face shortages of forest materials. Most of these countries are unable to shift their energy consumption to alternative energy sources like oil. Even though two of the countries (i.e., the Democratic Republic of the Congo and Nigeria) are major producers of oil, they are still dependent upon their forests for rural energy production; oil is an important export commodity that maintains these countries GNP and, therefore, in-country energy production is a lower priority (Vogt et al. 2010a).

The data suggest that Guatemala has the potential to use its forests to provide energy but will face severe challenges to continue this practice. Similar to the other countries, Guatemala has high deforestation rates, and reforestation is not occurring at rates able to compensate for its forest losses. Much of this forest loss is part of the land-use changes to grow oil crops like palm oil or sugar cane by regional elites; this decreases the supplies of forest materials for local communities, who have fewer alternative options to produce energy.

The relative amount of energy consumption from forest materials and renewable materials is graphed against each country's HDI rank and its population density in Figure 1.6. This comparison shows how Guatemala is similar to a number of the other low-latitude countries where there is a strong dependence on forest and renewable energy sources, a relatively high population density, and a low HDI. These characteristics will make it challenging for any country to pursue sustainable economic development options because it is difficult to simultaneously resolve each problem in isolation from the other factors that constrain development.

Land-Uses and HDI Rank

It is valuable to compare the current land-uses in Guatemala to the other 34 countries to place Guatemala's current land-use into the context of other countries and to consider whether its choices are sustainable (Figure 1.7). Currently, Guatemala has 34% of its land in forest-cover. This amount of forest-cover is low when compared to other countries that are dependent upon their forests for energy. The amount of forest-cover in Guatemala has significantly decreased over the last two decades due to high deforestation rates. Between 1990 and 2010, Guatemala had a 23% decrease in its forest-cover; this is an average decrease of 1.15% forest-cover per year (FAO 2010; Mongabay.com 2012).

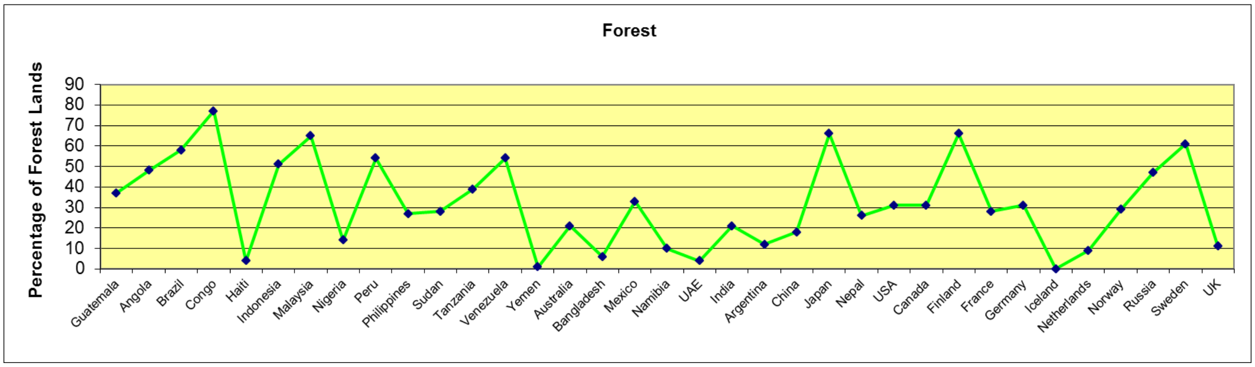


Figure 1.7. Percentage of forest lands in the 34 countries studied by Vogt et al. (2010), and Guatemala.

When compared to the other 34 countries, Guatemala has a high portion of its lands classified as arable + pasture lands (42%; Figure 1.8). These lands are less likely to be converted to growing biofuel crops because they are needed to grow food crops or to raise animals for food. In fact, this portion of the land in arable + pasture lands has not significantly changed in the last 20 years in Guatemala (Trading Economics 2012). If Guatemala is to convert these lands for biofuel production, it would require them to import food products, which is not a realistic option under the current economic situation.

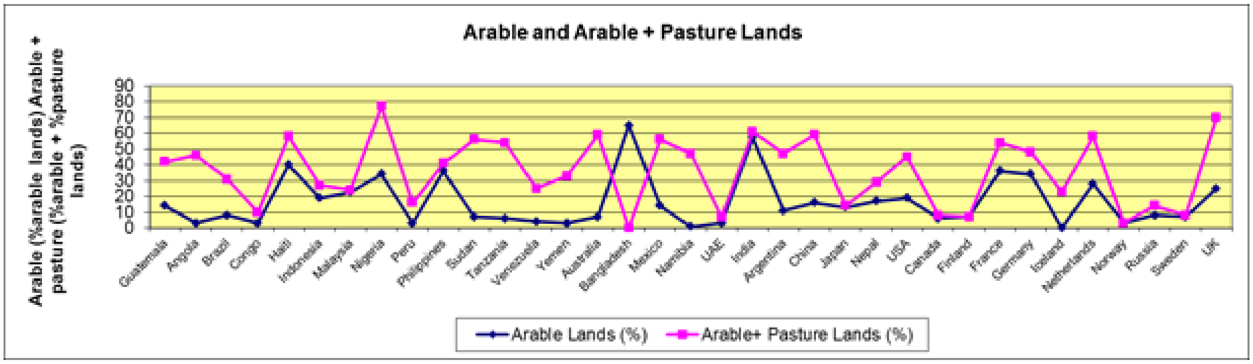


Figure 1.8. Percentage of arable lands and arable plus pasture lands in the 34 countries studied by Vogt et al. (2010a) and Guatemala.

When the amount of forest, arable, and pasture lands are plotted against HDI and population density (Figure 1.9), Guatemala's lower HDI and high population density suggests that it has few options available to use its lands to improve the livelihoods of its people. Guatemala will have to balance its current uses of its lands in order to ensure that land-use choices do not decrease its ability to pursue options for increasing its HDI rank and to feed its population, which is growing at a rate of 2.6% per year (Mongabay.com 2012).

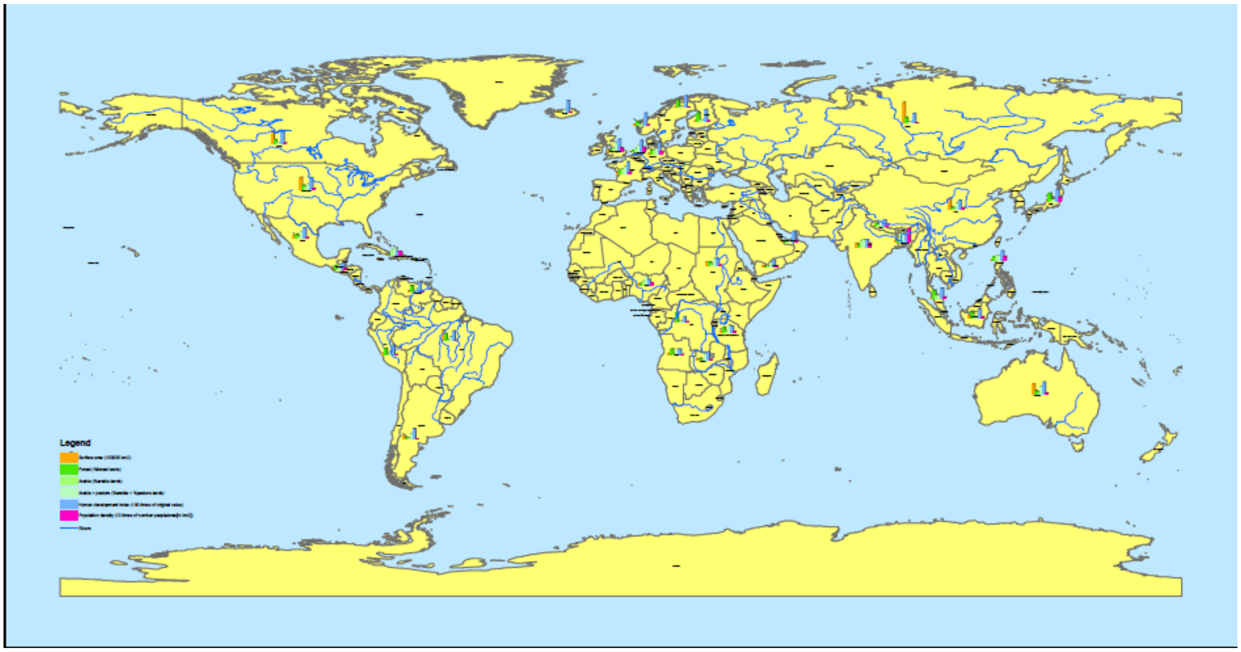


Figure 1.9. Map with bar graphs in the 34 countries studied by Vogt et al. (2010a) and Guatemala to show their relative forest, arable, arable and pasture lands, along with surface area, HDI, and population density

When forest area decreases, there are multiple impacts on local communities as well as on the continued delivery of ecosystem services the global communities would like to acquire from forests. As expected, the higher the amount of carbon stored in a forest, the higher the percentage of the total CO_2 emissions that could be sequestered by a growing forest (Vogt et al. 2010b). The international communities have been trying to determine how to balance producing energy products and reducing carbon emissions, while also providing livelihood possibilities for local communities.

Soil Chemistry Constraints to Plant Productivity in Wet Tropics

Most lands have soil constraints that reduce crop growth. Knowing the chemical constraints, especially, is the key to plans for improving the crop productivity while safeguarding environmental conditions (Vogt et al. 2010a). Soil chemistry should determine what management practices can be implemented to increase crop production and what toxic constraints imposed by it cannot be offset by existing tools. Obviously, when farmers cannot compensate for their soil constraints, it will be more difficult for them to grow a sufficient quantity of food crops locally.

Soil development is a product of climate, parent material, topography, time, and organisms. Soils may be water-saturated or well drained, shallow or deep; the parent material may be bedrock or unconsolidated sediment, fertile or sterile; and they may have low to high water retention capacity. The features together affect:

- erosion potential of the soil;
- the type, abundance, and productivity/growth rates of plants;
- type of plant that can grow on any land, the composition of native/non-native species and how competitively plants are acquiring resources needed for growth; and
- the nutritious quality of plants consumed by grazing animals and humans.

With sufficient time, climate has a dominant influence on the depth and intensity of weathering and, therefore, the nutrient status of a soil (Brady 1990). Compared to temperate climatic regions, tropical wet climatic regions have the greatest depth of weathering of their parent material mainly due to high precipitation rates and high temperatures. In these regions of the world, most of the original essential plant nutrients that existed in the parent material have been weathered and leached below the rooting zone of most plants. For example, some of the Brazilian rainforests have tree roots, with their symbiotic associations, growing to depths as deep as three meters, where the soil nutrient concentrations are higher. The wet tropical forests have also adapted to recycle nutrients within the vegetative biomass itself; e.g., 40-cm-deep mats of roots and symbionts grow on the surface of the soils and collect minerals leached from senescing plant tissues. This recycling of nutrients within vegetative biomass itself can almost isolate a plant from needing to acquire soil nutrients (Vogt et al. 2010a).

The Food and Agriculture Organization (FAO) (2000) identified eight soil characteristics that can constrain plant productivity. These constraints are those that are most likely to result in low-soil productivity, slow plant growth, or dominance of sites by those plants adapted to mitigate the constraints imposed by these soil characteristics. Farmers have to consider, or adapt to, several of these constraints simultaneously. The eight soil constraints are:

1. Hydromorphy – poor soil drainage
2. Low cation exchange capacity (CEC) – low capacity to retain added nutrients
3. Aluminum (Al) toxicity –elemental toxicity and strong acidity
4. High phosphorus (P) fixation – insoluble complexes of phosphorus with ferric and aluminum oxide (in acidic environment) or of calcium oxides and hydroxides (in alkaline environments)
5. Vertic properties – clays that contract and expand with moisture changes
6. Salinity and sodicity – presence of salts and sodium in solution
7. Shallowness – shallow soil depth with bedrock near the surface (less rooting volume available)

8. Erosion hazard – high risk of soil erosion due to steep slopes or moderate slopes but also erosion-prone soils due to texture, mineralogy, organic matter, climate, hydrology, etc.

The most difficult soils to manage are those where aluminum (Al) levels are toxic to plant growth; soils with higher Al also tend to have low base cations and are highly acidic. These factors reduce plant productivities. Countries that standout as having major problems with Al toxicity are all found in the tropical climatic zones, including Guatemala. Consequently, these countries face serious challenges relative to their food production, especially as their population continues to increase. Some agricultural plants, especially root crops, grow well in soils with higher Al levels (e.g., yams, pineapple, and tea) (FAO 2000). Soils high in Al are difficult to manage using fertilizers; they could be improved by the addition of lime, but generally these countries with Al-rich soil do not have sufficient and also inexpensive supplies of lime (FAO 2000).

Farmers have effectively managed other soil constraints, such as nutrient deficiencies and water supplies, most commonly by irrigation (or drainage) and/or fertilizer. Although there seemingly is little correlation between the ability to manage these two factors and the degree of country development, extents of irrigation and external fertilization reflect a country's priority for increasing the productive capacity of its lands.

Severely degraded lands tend to be in countries that are less developed economically. The productive capacity of soils is based on several factors, all of which must be considered if degraded lands are to be utilized more efficiently, or indeed, if the other lands are to be more productive. Soil fertility and water-retention capacity involve more than applying fertilizers, for they are influenced by the organic content of the soil, its acidity, texture, and depth (Gruhn et al. 2000).

Agriculture has evolved to a sustainable science - where crops can be grown with minimum negative environmental impacts. However, these principles are not always applied effectively, especially when and where a country faces growing population with limited additional area that can be dedicated to crop production.

Because local soil constraints (e.g., Al concentrations) commonly result in food production with limited nutrient value, the inhabitants in those areas need to be able to consume food produced elsewhere under different conditions. Also, with large commercial farms, it is common for a limited number of food types to be grown locally or even over large landscapes, thereby increasing the need to import food supplies from other regions of the world better able to grow a diversity of nutritious foods. Conversion of land with native vegetation and domestic farmlands to banana and oil palm plantations is commonplace in much of Guatemala that is arable.

Reducing carbon footprints in food production must address the fact that all soils are not of equal quality/health and that for healthy food supply, transportation is necessary. Soils that develop in one area may allow plants to grow quickly and still produce food crops that are nutritionally well balanced, but in other cases, the soil may not grow sufficient food crops or it may grow crops that are not very nutritious. Most soils have probably developed to stages that are intermediate between these two extremes. It is difficult to manage soils that have lost much of their productive capacity and to manage soils on lands that are poorly suited for farming. Ideally farming practices should include careful consideration of soil development and suitability for particular types of food, in addition to the nutritional needs of the inhabitants and the environmental impact. Management practices should also be consistent with the fact that soils and local climate control what practices can be implemented to increase food production and yet be sustainable. If cultivation is not favored by soil constraints, other uses of the soil should be employed (e.g., ranching).

The health and productive capacity of a soil is a critical factor for the welfare of countries and the well-being of its people. Soils develop (evolve) through time, and these changes are determinants of their productivity and the adaptability for growth of specific types of plants. As the soil becomes older, it becomes more nutrient-poor and contains more chemicals toxic to humans and plants. This is the situation in the wet tropics where soils have lost much of their available nutrients over a span of thousands of years of heavy rainstorms (Sanchez 1976). This means that many of the tropical areas have limitations on which crops can be grown, and shifting agriculture has to be practiced that allows the soils to renew themselves. The fertility of a soil is an important challenge facing those pursuing sustainable agricultural practices in lands that are already severely degraded or where the soils are old (Gruhn et al. 2000).

Globally, only one-fourth of the world's land has soils that lack only one of the eight major constraints critical for defining a soil's fertility (FAO 2000). These regions correspond to the world's leading grain-producing countries. Two countries of a pool of countries studied with major constraints represent, respectively, arctic and desert conditions. The study also shows that one-half of the countries have more than 80% of their land with some major soil constraint and that all the countries have soil constraints that decrease crop productivity on at least 50% or more of their arable land. Generally soil constraint needs to be countered in order for crop production not to decrease.

Water Footprint

A rational Life Cycle Assessment (LCA) of water determines the total amount of water used by the production system from beginning to end (e.g., Humbert 2010, Lundin and Morrison 2002). The requirements for determining the sustainability of the water supply are renewable water sources (influent or LCA inputs) and adequate quantity (resource) and the quality of the water released (effluent or LCA output) in terms of utility by humans or ecosystems. There are multiple links of fresh water to energy production and consumption because of the link between renewable resources and the use of agricultural materials. Currently, agriculture requires approximately 85% of the world‘s freshwater demands (Hoekstra and Chapagain 2007).

Today the connections between water, energy, and agriculture are being further exacerbated because of the demand for green energy using agricultural practices. The main driver for land conversion today is the transfer of more land into agriculture for producing biofuel crops. This trend has been well documented (Bringezu et al. 2009). Not only is there an increase in the production of biofuels, but this energy demand is driving increasing water consumption by the agricultural sector. Because most of the land conversions are going from a forest condition to agricultural fields (German et al. 2010), the loss of forest lands will ultimately result in decreasing water supplies since more than 60% of fresh water in the U.S. originates in forests (American Forests 2012). This has the potential to increase the conflicts over water supplies. Most of society's history of this world has revolved around conflicts and war over water supplies (Gleick 2008); in the past it was for food production, while today it is for energy. Energy, regardless of its source, requires a fresh water supply for a multitude of reasons; this relationship is commonly overlooked when decisions are made regarding energy consumption or production.

The water footprint, described by Hoekstra and Hung (2002), calculates the water needs for consumer products. It distinguishes the source and the quality of water, and it may be used to assess the water footprint per unit of energy from a particular energy source. The water footprint itself includes three types of virtual water (green, blue, and gray). Virtual water is the amount of water needed to produce a certain product. Green virtual water is the rainwater that evaporated during plant growth; blue virtual water is the irrigated water that evaporated during plant growth;

and grey virtual water is water that is polluted during the process of producing the final product. Compared to 33 other countries, Guatemala has a water footprint, suggesting water consumption per individual is not an option to reduce (Figure 1.10). This footprint shows the traditional water consumption habits for Guatemala; it does not reflect how its footprint has changed to the recent planting of palm oil and banana plantations. It also does not reflect the changes in water quality due to the increased use of fertilizers and pesticides needed by intensive agricultural practices.

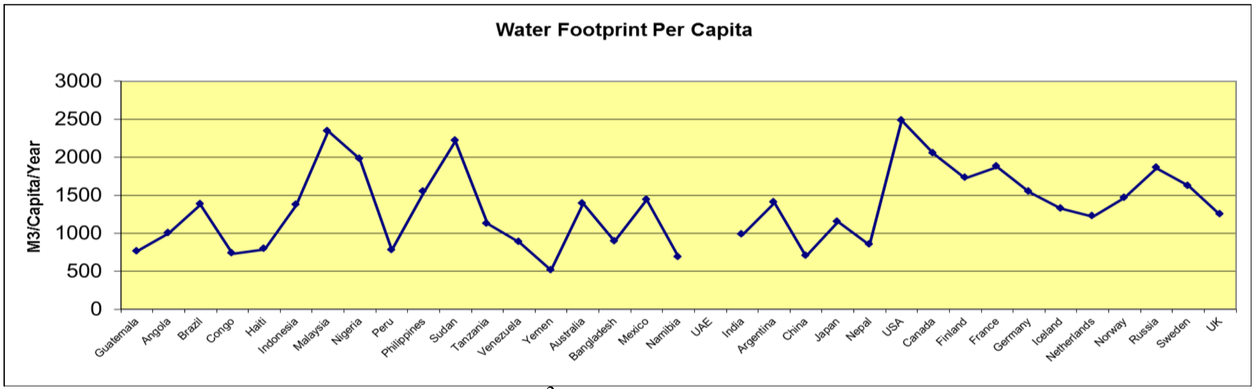


Figure 1.10. Water footprint per capita (M^3/capita/year) in 33 of the 34countries studied by Vogt et al. (2010a) and Guatemala.

Of particular interest for this study is the water footprint for biomass, which is based on the mixture of plants, the pertinent agricultural practices, and climate (Gerbens-Leenes et al. 2009). These authors show that the footprint of bio-ethanol, for example, is smaller than the footprint for biodiesel. If only the water footprint is considered when making decisions related to energy, it may be more efficient to produce electricity than to produce a biofuel. Of course, climate, with temperature and rainfall as the main factors, is critical, for both generation of energy and plant production. The data in Figures 1.4, 1.5, 1.7, 1.8, 1.10, 1.11, and 1.12 reflect the close relationships between water, energy, and plants. In the case of Guatemala, another factor is important: the very uneven distribution of precipitation throughout the calendar year. Additional use of plants for energy would necessarily require water supplies, just as plantations have required additional supplies. These parameters must be considered separately and together in order for arrive at sustainable solutions.

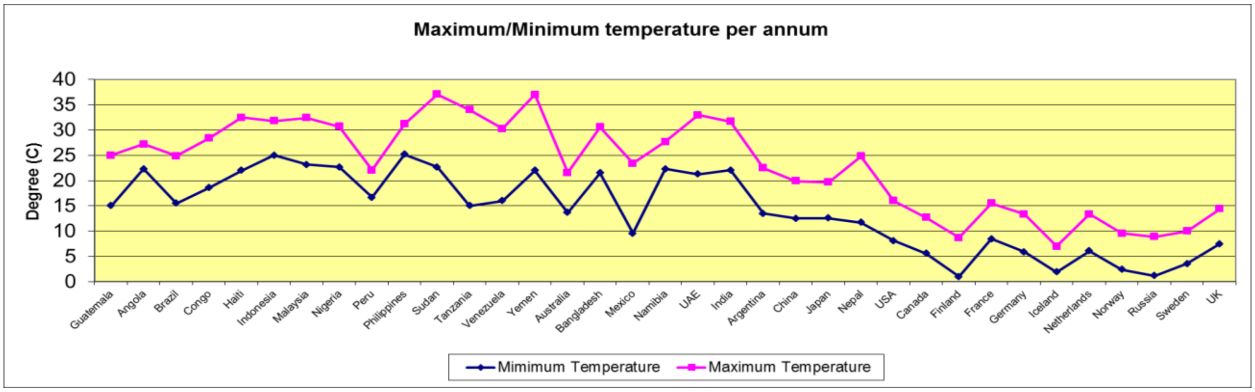


Figure 1.11. Average minimal temperature and average maximal temperature per annum (degrees C) in the 34 countries studied by Vogt et al. (2010a) and Guatemala.

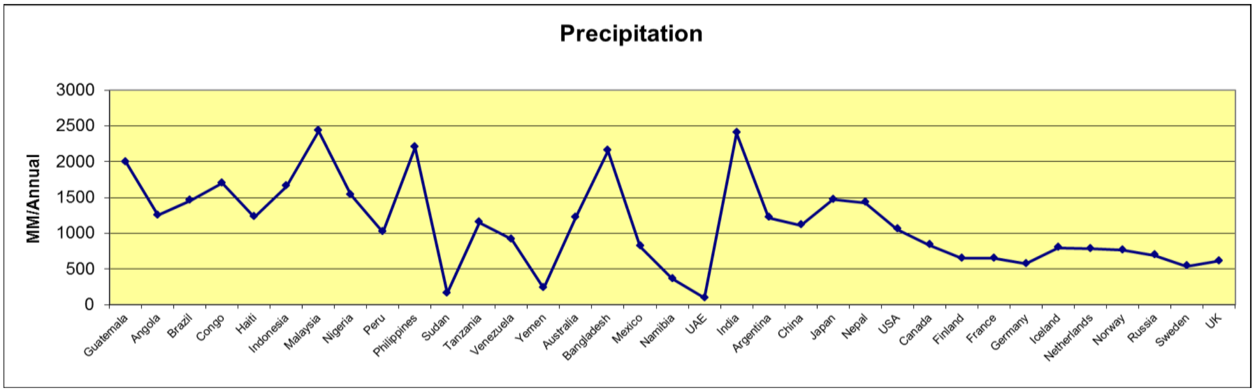


Figure 1.12. Precipitation in the 34 countries studied by Vogt et al. (2010a) in mm per annum, along with precipitation in Guatemala.

To assess a country’s water supplies, the renewable water resources need to be separated into those that are sourced outside the country and those that are sourced and recharged from within its boundaries. A country with 60% or more of its water supplies originating from outside sources is considered vulnerable to water insecurity, although rainfall data and river-discharge data must be considered along with the water-source data in order to assess the water security properly. Figure 1.13 shows the water footprint in the countries, as noted above. Guatemala derives essentially all of its water from within its boundaries. Although rainfall data might suggest that it has a high water security and low risk of desertification, the annual extended dry season indicates short-term desertification is a real risk.

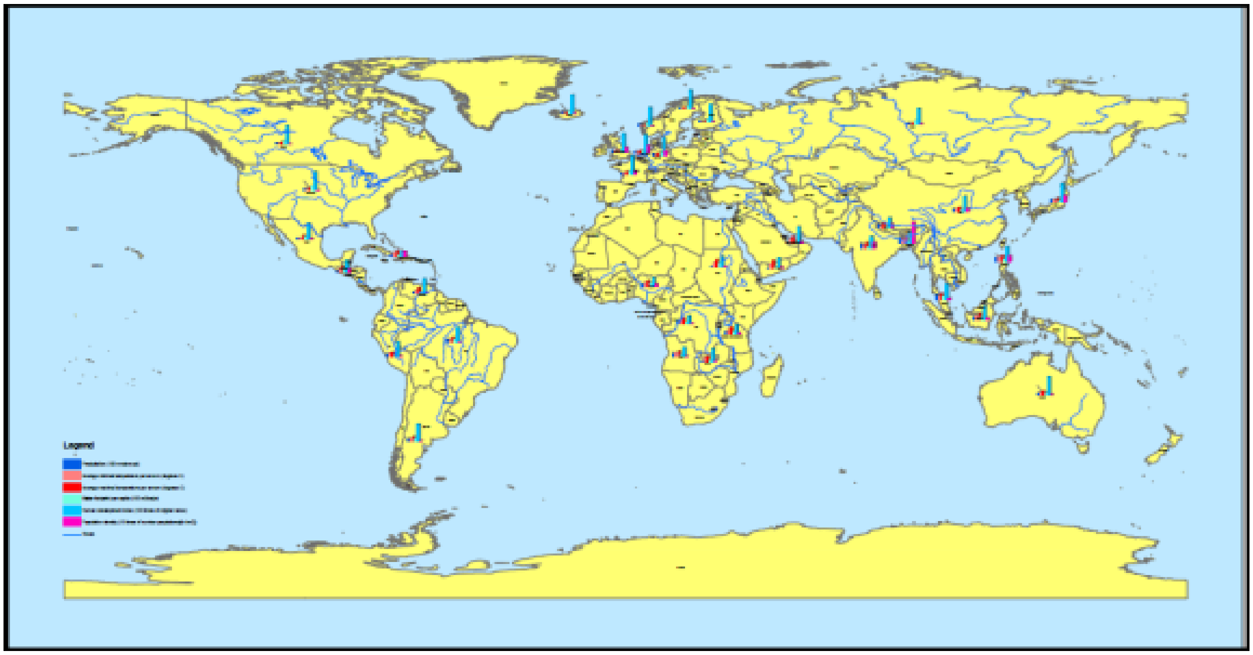


Figure 1.13. Map with bar graphs in the 34 countries studied by Vogt et al. (2010a) and Guatemala to show their relative minimal and maximal annual temperatures, annual precipitation, water footprint, HDI, and population density.

Climate and Food

The amount of land allocated to agriculture by a country is dependent largely on climate and soil characteristics, which in most cases are also heavily dependent on climate (refer to Figures 1.11, 1.12, and 1.13); factors like the degree of technology utilized and population demands will also impact how much land is in agriculture (refer to Figures 1.2, 1.5, 1.9, and 1.13). Today, the region where Guatemala is located experiences high temperatures (Figure 1.11) that decrease the efficiency of agricultural production because of the water demand. Rainfall levels are high in Guatemala (Figure 1.12) today, but seasonal data and history suggests that this region of the world is susceptible to severe droughts. During the Medieval Global Warming period, this region of the world became considerably drier and caused the collapse of several civilizations (Neff et al. 2006, Fagan 2008). Modeling exercises have suggested that the temperature may not change in this region of the world, but these areas will become drier (e.g., Stecker, Tiffany, and Climate Wire 2012; Pal et al. 2007). Therefore, history suggests that Guatemala needs to make choices that do not reduce the ability of its society and environments to be resilient to drier climatic conditions.

When the water footprint, annual precipitation and HDI are plotted onto a map (Figure 1.13), the relation between the high annual precipitation and the low water footprint suggests that the solution to increasing the HDI is to increase water consumption; for supplies appear plentiful. However, the lower HDI suggests that the total water footprint will only increase if economic activity is to increase. Therefore, if Guatemala transitions closer to the industrialized countries, water shortages are likely, especially inasmuch as they are located in a region of the world where climate change historically has resulted in droughts.

In addition to potential climate change, the annual high rainfall and its distribution through the year reduce the productive capacity of plants in Guatemala. It will determine how much food can be grown in Guatemala, how much food has to be imported, and how rapidly trees will regrow and re-establish previously harvested forest cover. These relationships indicate that soil chemistry will constrain the options that exist in Guatemala, and it should be factored in when making decisions related to converting forests and other lands into palm oil plantations or other oil or food crops.

The practices that make a soil degrade and those that are unsustainable are well known by agronomists. However, this is less understood by the general public living in the industrialized world, as well as people living in developing countries. In contrast to soils, there appears to be a general appreciation of the influence of climate on plant growth and the need to manage soils. In countries with a large proportion of the population involved in growing food, there is a general understanding of soil constraints (refer to Figure 1.2, which shows population density, and Figure 1.3, which is a plot of the surface areas of the 35 countries). The survival of those people depends on understanding how to mitigate soil and climate constraints to plant growth. These people are mostly impacted by climate and weather; for they cannot control those unpredictable events. Many past societies have effectively adapted to the constraints posed by their soils; some practices developed in the past work so well that they are being considered for adoption today. Soils generally reflect the legacy of past human activities as well as the constraints that will impede the land's productive capacity.

Soils are essential for human and ecosystem survival. They determine the amount of bio-resources humans will be able to collect and the difficulty in maintaining the services rendered by the land in question. This situation is particularly important for Guatemala because of the significant changes occurring in land-uses and the practices being implemented to maintain soil productivity, e.g., fertilization and application of pesticides. Soils have a memory of past practices and accidents they have experienced.

As the population increases and becomes more urbanized, with the resultant decrease in a direct connection to agriculture, the role of soils becomes less ingrained in the people. Soils are the medium used to grow our food, and they provide the essential nutrients. Soils are also the sites where renewable energy supplies can be grown (e.g., biomass). When people do not have a choice to migrate from lands with degraded soils to more productive lands, the ultimate impact of using degraded soils may result in their being unable to support the larger population densities that have become dependent upon them (refer to Figure 1.2). Historically, this set of circumstances has contributed to the eventual collapse of a community (Hillel 1991).

Today, these soil constraints are being further aggravated by changes in water supplies. More than half of our fresh water is derived from forests (MEA 2005); excluding Alaska, two-thirds of the runoff in the U.S. is from forested areas (Sedell et al. 2000); these data indicate that any decrease in forest area will decrease water capture by forests. Furthermore, energy production can have a high water demand. So our demand for energy should have significant repercussions on future food production and the delivery of ecosystem services like fresh water.

Energy and Water

Today, the more recent drivers of deforestation are the conversion of tropical forests into sugar-cane fields, soy fields, or palm-oil plantations (e.g., Worldwatch Institute 2012, Chazdon 2008). These are biofuel crops and are being used to produce ethanol or bio-diesel, as well as providing traditional food supplies. Expanding the land area in these biofuel crops is occurring at the expense of forest cover because other lands are not available for these purposes. Forest lands also have more productive soils than some of the other lands; consequently, they are considered logical lands to convert to these energy crops.

When a society makes energy choices, it is also impacting other resources needed for human survival. When food crops are used to produce biofuels, for example, there is competition for that resource, with the result being food shortages; these have been a common topic of discussion in newspapers and journals and have been summarized by international organizations like the United Nations. Alternative fuels or green fuels (to fossil fuels) commonly result in increased pressure on freshwater resources.

These increased pressures result from either the increased demand for freshwater resources by more consumers or contamination of these resources with intensive agriculture, including large tracts of monoculture plantations where prior use was non-intensive and non-extractive use (e.g., Carrere et al. 2012). It is not uncommon to record water contamination when large tracts of land are converted into intensive agricultural plantations that require fertilizers and pesticides to maintain their growth rates (e.g., Ongley 1996). Intensively managed plantations are also not economical unless the growth rates are optimal to maintain the supply chain demand by the conversion technologies and the markets. Furthermore, a considerable amount of water is consumed to achieve the productivity of the resource that contributes to conflicts over the available water supplies (Gleick 2008).

It is useful to compare countries in how they consume energy, their water footprint, and how they are correlated to the human development status. Such a comparison begins to (a) identify the supply and demand for energy and water and (b) inform the reader whether any country is making sustainable choices related to these resources, or whether they will have difficulty satisfying an increased demand for both resources. Such an analysis sets the context for each country and determines if it has the potential to achieve its goal of becoming a producer to supply alternative energy products to consumer countries without reducing its in-country social and environmental resilience.

To assess the potential for a producer country to increase its production of green energy products without detrimental social and environmental repercussions, it is critical to understand the connections between green energy production, water, and the human development capacity. Understanding the current competitive demand for resources within a country is important to know in relation to other countries. This clarifies the choices that a country has been making related to its resource uses, indicates whether renewable resources are extensively consumed, and records how much existing business enterprises consume these resources (Vogt et al. 2010a). Inasmuch as the focus of this study is Guatemala, data for Guatemala has been added to the original data base for the 34 countries studied by Vogt et al. (2010a) to derive water and energy indices at the country level.

Because landscape changes are being driven mostly by deforestation and land conversion to intensive agricultural production, it is important to understand the role of forests in providing energy and its environmental benefits or ecosystem services. The loss of these ecosystem services (e.g., Laurance 1999; Chiabai et al. 2010) has ramifications for social resilience at the community level. Therefore, it is important to briefly discuss the current land-uses, what level of deforestation is occurring - so that the loss of forest lands can be evaluated, as well as the amount of forest materials that may no longer be available for local energy consumption in view of the international metric for climate-change mitigation, e.g., carbon dioxide emissions due to deforestation and the loss of C credits or revenue by tropical countries, such as Guatemala.

Deforestation, CO_2 and Land-Use Changes

Today, land-use change by deforestation is of more of a global concern than in past years because of the resulting increase in CO_2 emissions into the atmosphere and the purported impact of increased emission of greenhouse gas (with CO_2 being one of the significant gases) on climate change (AIP 2011; Bureau of Meteorology 2012). Forests are important locations of carbon storage and locations for short-term carbon storage and mitigation of the fossil carbon emitted by industries (e.g., Gorte 2009). This carbon storage by forests is not possible when deforestation rates are high. This obviously is a global problem, and deforestation rates in countries with higher areas of forests are important to the global community. Four countries contain more than 50% of the global forests, and three of them (Brazil, the Democratic Republic of the Congo, and Russia) are experiencing high deforestation rates.

For the 35 country database used in this study, information on the amount of forest lands and arable and pasture lands is useful for comparison in order to understand how much land is already being utilized, how much might be potentially available for resource extraction, and how much is available for conversion to other uses (Figures 1.7, 1.8, and 1.9). Even though Guatemala contains only a very small percentage of the global forests, today 34% of its land is in forests (a slightly higher percentage than what exists in the US) (Vogt et al. 2010a). Guatemala has been reported as one of the many countries where land-uses contribute significantly toward the total CO_2 emissions and where deforestation rates are high. Growing-economy countries, including Guatemala, consistently have significant portions, commonly more than half, of their CO_2 emitted during land-use changes (Vogt et al. 2010a).

New options are emerging for retaining forests while using them to produce biofuels. Over the last couple of decades, the goal of the international community has been to develop solutions where forests are not cut-down but used efficiently to convert to energy products (Vogt et al. 2008). Inasmuch as forests are highly productive, this is becoming a realistic and viable option to pursue, for it would retain forest canopies. Forest materials, because of their chemistry, are also able to be converted into liquids that are used in fuels. For example, methanol, a one-carbon alcohol, is used to supplement or substitute for gasoline or to power appliances. Unlike fossil fuels, forests not only supply products and services essential for human survival and provide habitat for many other animals; they also represent renewable resources. Forests have multiple functions - both during and after the trees are alive. Fossil carbon cannot provide these services; it is not renewable in a human’s life span.

Technology to transform biomass into useful liquid or gas products has recently become sufficiently efficient to provide, under certain conditions, an alternative or supplement to fossil fuels. This is a significant factor because it decreases the net greenhouse gas emissions and helps decrease the Unites States' dependency of foreign crude oil. Mousdale (2008) has documented how a large number of materials and products can be produced from methanol – a liquid fuel efficiently produced from forest materials.

Dependence on fossil fuels seemingly will continue for the foreseeable future, as the countries are becoming, or have recently become, fossil-fuel-based economies. However, many countries are attempting to limit their CO_2 emissions by using renewable resources, including biomass, some of which is from forests. Because Guatemala has 34% of its land in forest cover, this is an option for them to explore. Whatever solution Guatemala adopts should not decrease the resiliency of its people and the environment.

Although several approaches exist to convert agricultural and forest biomass or wastes to liquid, some biomass materials are more efficiently and economically converted to ethanol or methanol because of their chemical compositions. For example, wood biomass is not an ideal material to convert to ethanol until cellulosic wastes can be converted efficiently to sugar compounds. The efficiency and economics of conversion are important factors because the amount of CO_2 emissions avoided depends on how much energy and fossil fuels are needed to produce the product compared to its energy content. The recently high efficiencies of conversion of wood biomass to methanol and the need to thin forests to reduce fire risks make further exploration of the various ways bio-methanol can mitigate CO_2 emissions a high priority (Vogt et al. 2009).

The conversion of biomass to biofuel provides greater environmental benefits than if the biomass is untouched or is discarded as waste. In the case of forests, collection of waste materials and/or use of small-sized stems and limbs of trees is required - not extensive cutting of trees. Removal of biomass materials from our landscapes is desired not only because excess mass and marginal wood contribute to forest fires, but also because the fires are commonly associated with subsequent floods, and insect outbreaks in many regions of the world. Unfortunately current practices too often are prescribed burning within forests or transportation of biomass wastes to landfills (e.g., West 2005, Lyns 2012). In the latter case, burial reduces atmospheric CO_2 - only for a period of time until methane or other C-bearing gases escape or until CO_2 returns during decay (Vogt et al. 2010a). Neither one of these options is good for the environment or public health. Also biomass materials should be removed from our landscapes to practice conservation, to eliminate woody invasive species, and to restore forest environments.

In regard to non-forest biomass, the preferential use of agricultural crops to produce biofuel is a complex problem because of the potential for destabilization of food supply, associated prices, and to some extent energy supply/prices. Also, degradation of forested areas, due to their conversion to crop growth, presents yet another problem. The overriding factors should be:

- The requirement that the biofuel production is sustainable.
- Use of the sources results in an increase in net energy and decrease in CO_2 emissions.
- Any change in land-use does not result in additional problems with soil erosion, flooding, or water pollution.
- Use should not result in significantly higher food prices or food scarcity.

All biomass types - not just agricultural crops - should be considered as the starting material to produce biofuels. This substantially increases the source base and lessens the impact of some of the problems noted above. All sustainable biomass sources should be used, and the biomass source selected should be locally available. Each location may need to determine its own unique biomass type in order to eliminate its own unique environmental problems. For example, in the western United States, total state carbon emissions can be reduced by approximately 20 to 80% if bio-methanol is substituted for gasoline (Vogt et al. 2009).

When and where forest fire risk is high and where most of the energy produced is from fuel wood (as in developing countries), converting that wood to bio-methanol for the production of electricity is an attractive alternative. In Indonesia, using bio-methanol from forest materials to produce electricity and as a gasoline substitute has the potential to reduce total carbon emissions by about 10% to more than 35% (Suntana et al. 2009). This is an option that countries such as Guatemala should include in their portfolio of energy options. Yet this seemingly is not one of the options that are being pursued in Guatemala even though it is ideally suited for this option because of its existing extent of forest.

Environmental Challenges, Food Security, and Land-use Change

Droughts are the most common disturbance that affects soils. With increasing population and its associated demand for resources, such as water, and with uncertain climatic conditions, the potential for reduction in the productive capacity of a soil is a serious problem in some parts of the world. This is a problem especially in areas where a high proportion of people are involved in agriculture.

Even though most people do not make the connection between sufficient food supplies and soil quality or the impact of their land-use activities on the soil, they are concerned with whether enough food can be produced to feed everyone. Despite the dire predictions of Thomas Malthus (1798) about population growth resulting in poverty, human suffering, and environmental degradation, the Green Revolution allowed food production to keep-up with population growth. However, increasing demand of food production today applies additional stress on the soil and increases the risk for a decrease in soil productivity, i.e., less food grown on the same piece of land.

In many cases, increased food production by stimulating plant growth rates requires practices that result in the nutrient-supply capacity exceeding the soil supply capacity. This practice needs to be implemented carefully because there are potential negative environmental conditions associated with them. To increase crop production, chemicals are applied to add nutrients and also to control undesired plants and pests. In combination the desired object is to achieve all three without damaging the soil. Nitrogen (N) fertilizers potentially have a greater impact on ecosystem health than many of the other practices implemented, especially when nitrogen is not in an organic compound. Nitrogen is an integral part of the enzymes that fix carbon during photosynthesis, but it also determines plant herbivory rates and microbial growth rates. Excessive nitrogen tends to impair the health of the soil ecosystems, to increase the growth rates of weedy or exotic plant species, and to stimulate higher herbivory rates. Also excessive nitrogen may result in water pollution and human health problems resulting from nitrates in ground water. The higher N applications have indirectly altered the availability of other nutrients in soils because nitrate-N can increase soil acidification rates and, thereby, cause the leaching of basic nutrients (e.g., calcium) from soils (Wild 1993).

Over-fertilization by application of excess animal waste has resulted in eutrophication of streams and lakes (e.g., Zheng and Paul 2006). Today, the biofuels industry (e.g., ethanol produced from agricultural crops, bio-diesel from palm oil) is also contributing to eutrophication of bodies of water.

Resilient Tropical Landscapes and Bio-Resource Supply Security

Country-level decision-makers are searching for solutions to the unavoidable constraints of plant and soil productivities that are economical. One of the choices available to them is to import resources from another country or countries better positioned to produce the product or products.

As Hoekstra and Chapagain (2007) note, this is an approach in which a country can shift its production of food from those areas with low productivity due to soil and/or water conditions to countries with better conditions. This, of course, would increase the efficiency of global soil and water use. The most important factor in the limitation of this practice is droughts, which are more devastating than other extreme weather conditions, earthquakes, or volcanic eruptions (Below et al. 2007). Technology also enters the picture - use of additives for plant-growth enhancement and improvement in water quality and availability.

Although climatic limitations and soil-quality differences determine whether locally grown food will be nutritionally adequate to maintain human health, today with the global commerce involving food items, the more prosperous humans have access to a wide variety of food year-round. Yet some countries prefer to support domestic crop production in order to ensure food security, Japan, for example. There, limitations exist in terms of quantity and variety of products because of limited land area and homogeneous soil type due to common parent material (volcanic products).

Another issue in global food production that can limit food security is contamination by chemicals and/or microbes. However, food contamination is not just confined to food produced for global consumption; it also can occur anywhere industrial quantities of food are processed. If the general public is to be better fed and obtains a more nutritious diet, globalization of food production is the ideal system.

When life-cycle assessment (LCA) is applied to essential resources - food, energy, water, forest materials - it is essential that constraints for each resource be identified; it is also essential to understand how decisions made for one of the resources needed for human survival affects and impacts the sustainability of another need (Vogt et al. 2010a). A life cycle approach would be quite cumbersome if it needed to include all human survival needs, and data are lacking to apply an LCA at the level where this analysis needs to be conducted (Vogt et al. 2010a).

The FAO (2003) defines food security as: “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. FAO (2008) suggests that all four components of food security must be adequate (e.g., availability, stability, accessibility, utilization) to achieve food security.

Today, it seems that food security should be assured, with all the advancements made in increasing the productivity of food crops (i.e., the Green Revolution). However, food riots and a rise in malnutrition occurred in 2008 because of food costs due in large measure to diversion of food crops to biofuel production (Tenenbaum 2008, Vogt et al. 2010a). This illustrates how sensitive both subsistence and intensive farming systems can be to external shocks. It also highlights that global food supplies are not secure, even today, despite the increased growth benefits that resulted from the Green Revolution. Increases in agricultural output in the 20th century can be attributed to horizontal expansion of arable land and the capacity to intensify production through the application of seed, fertilizer and pesticide technologies. Agricultural intensification was also stimulated by society’s ability to store, deliver, and pump surface and groundwater.

There are several reasons why agricultural production has been decreasing in the growing-economy countries. Soil moisture deficits and weather-related crop damage have been the predominant factors limiting agricultural productivity. Also, there is a link between poor health and not getting enough food; they are conditions in countries where civil unrest continues today. Poverty, political strife, and lack of investments in human and financial resources are contributing to food insecurities. In these countries, insufficient infrastructure for irrigation, storage, and transportation of water also have contributed to a lack of food security.

The Millennium Ecosystem Assessment (MEA) reported that people in the last 50 years have changed ecosystems more rapidly and extensively than ever before in order to meet our growing demands for food, freshwater, timber, and fuel (MEA 2005). Technology on its own cannot engineer food security, unfortunately; the future probably depends disproportionately on decisions that are not directly related to food security (i.e., political and population growth) but on unpredictable climate changes.

The earth's ecosystems varied from area to area before major changes to them by people and still vary from area to area even with those changes. Healthy and resilient ecosystems result from previous and current sustainable practices in regard to managing the basic resources. Human decisions as well as natural conditions, which are continually changing, determine resilience. Natural changes affecting the health and resilience of the ecosystem can be gradual, such as climate change, or they can be abrupt (e.g., earthquakes, volcanic eruptions, hurricanes, forest fires). The desired interaction between ecosystems and humans allow for economic resilience to the natural changes. Yet, local to regional areas of vulnerability will continue to exist (e.g., waterways, deltas and coastal metropolitan centers). Structures, such as dams, reservoirs, sea walls, stream diversion, may not prevent devastation. These clearly need to be constructed in concert with the natural systems.

Ecosystem adaptation, as the environment provides the necessary natural infrastructure, either by preserving or restoring it, is essential for human welfare. Biological capital, as well as the other elements of ecological systems and natural capital, should be carefully managed so as to ensure economic and personal well-being (Costanza et al. 1997). We can reduce the risk of our making ‘bad’ choices if we ensure that societies can remain resilient by using their solar capital (total amount of fixed carbon available for human use) that is managed environmentally (Vogt et al. 2010a).

Chapter 2: Environmental Characteristics of the Guatemala Study Site

Location and Description of the Study Area

The study area is on the Pacific coastal alluvial plain of Guatemala (Figure 2.1) and is located in the northern coastal area of Guatemala. Rain falls mainly during the summer and fall amounts to 2000 to 3000 mm annually at the coast and 3000 to 4000 mm annually on the piedmont. Relatively short rivers drain the highlands across the coastal plain, ending in biotically productive lagoons and mangrove estuary zones (Neff, 2006). Replenishment of soil nutrients on the coastal plain by air-fall volcanic ash and water-borne sediments contributes to high agricultural productivity. There is evidence of horticultural adaptation by the Mayans in this area between 1000 and 1500 BC (Beach, 2006).

Figure 2.1. Map of the study area in southwestern Guatemala. The three rivers flowing into the Pacific Ocean are (from the northwest) the Naranjo, Pacaya, and Ocosito.

Present-day agriculture consists of subsistence farming, primarily corn and beans, with plantation farming of African Palm trees and bananas. Historically, in terms of relatively modern times, corn and beans have been grown here, as well as cotton. There are still some cattle operations in areas near the wetlands where the soil is not as fertile and comprised more of clay. Some of the grazing areas have been converted to the palm plantations.

Guatemala's climate varies according to its diverse topography, ranging from tropical jungle in the northern lowlands, humid coastal areas, and cool central highlands. These three climate zones have very distinct characteristics. The climate of the lowlands is tropical, hot and humid year round. The average temperature for the coast ranges from 25° to 30°C, with daytime temperatures as high as 40°C (104°F) and nighttime as low as 22°C (70°F). The central highlands average temperature is 20°C and approximate 15°C in the higher mountains (World Bank, 2012).

The rainy season in Guatemala extends from May to October in the inland areas and from May to December along the coast, while the dry season extends from either November or January to April. Rainfall fluctuates between 1000 and 1200 mm annually in most of the country, whereas the Atlantic coastal area receives about 4000 mm annually. In almost all the country, the monthly values of evapotranspiration have little variation, ranging from 1300 mm/year to 1800 mm/year (MARN, 2004). Guatemala's patterns of precipitation and temperature are affected by fluctuations in the temperature of the surrounding oceans, the interaction of the atmospheric circulation with the Sierra Madre volcanic mountain ranges, El Niño/La Niña cycles, and intensification of the Inter-Tropical Convergence Zone (ITCZ) and Pacific Decadal Oscillation (PDO). The El Niño phenomenon magnifies vulnerability in the region, in particular, causing frequent severe droughts in the eastern portion of Guatemala (World Bank: Climate Change Portal, 2011).

Regional Precipitation

There are only five climate stations used for Guatemala's First National Communication to the United Nations Framework Convention on Climate Change (UNFCCC): Catarina (San Marcos), Retalhuleu, Río San José, Ipala, and the Mita Station. The station closest to the study area is Catarina. There is a lack of weather and climate monitoring capacity of the Department of Seismology, Volcanology, Meteorology, and Hydrology (INSIVUMEH), as noted by the (World Bank: Climate Change Portal, 2011). In addition, the density and number of weather stations are very limited, and some of the climate data was found to be incomplete or inaccurate and needed to be re-recorded. Given that caveat, the Catarina station is the best precipitation data available for the study area (Figure 2.2).

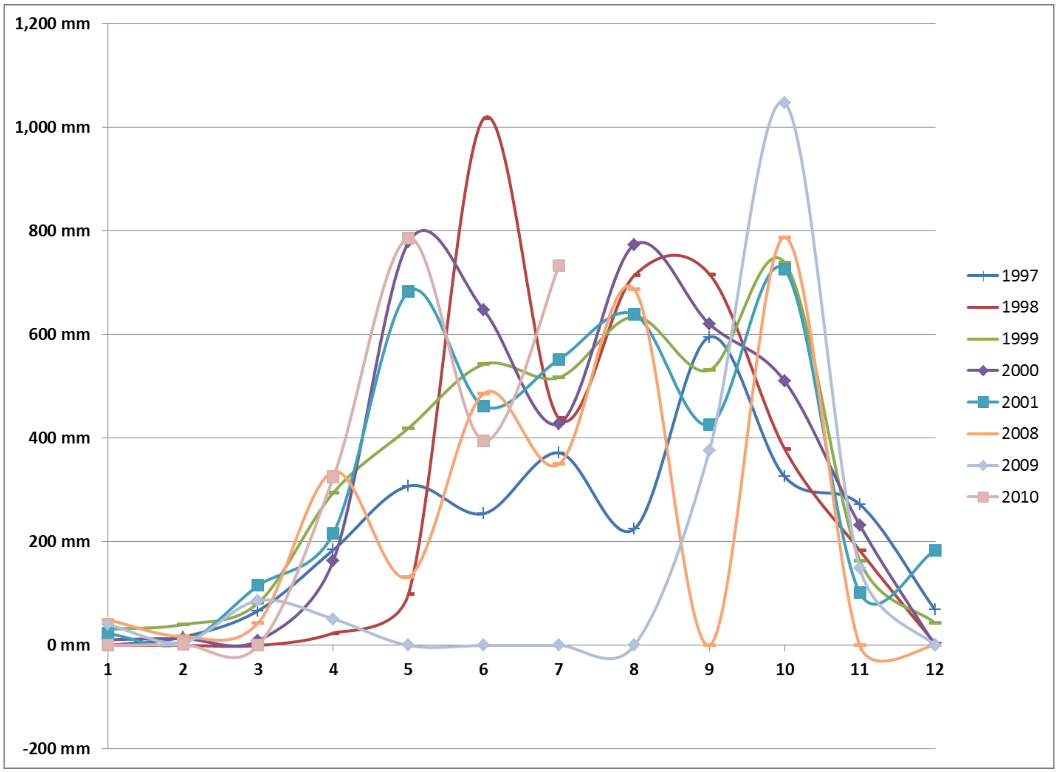


Figure 2.2. Monthly plots of precipitation for eight years between 1997 and 2010, recorded at Catarina, San Marcos, some 40 km north of the northwestern part of the study area. Source: Department of Seismology, Volcanology, Meteorology and Hydrology's (INSIVUMEH).

Climate Change

Guatemala has been identified as a region highly vulnerable to climate change. Its geographic vulnerability has been exacerbated by high poverty rates and poor environmental management (e.g., Drakenberg, 2006). A trend exhibited over the last 40 years suggests a more intense precipitation during shorter periods of time, thereby producing greater average precipitation per episode. This trend may continue in the future due to climate change; possibly the results will be greater frequency or intensity of both floods and droughts. This poses obvious impacts on agricultural production, soil, and land quality in addition to water availability and quality (World Bank: Climate Change Portal, 2011).

The World Bank estimates that by 2050, the following climatic changes will affect Guatemala and its agricultural sector: 1) temperature increases between 1.5°C and 4.5°C; 2) reduced precipitation; and 3) expansion of semiarid areas, given an increase in evapotranspiration due to temperature increase and a reduction in precipitation, the amount of semi-arid land will increase (World Bank: Climate Change Portal, 2011; Jara, 2010).

Land-Use

Historical Land-Use

As noted above, between 1000 and 1500 BC, there was horticultural adaptation by the Mayans in the Manchon area, which is located in the study area - in the present Ramsar wetlands (Neff et al., 2006). During this time period, there is evidence of shifting horticulture as an agricultural practice in the deciduous tropical forest by Mayan farmers. In more recent times, according to a 1947 Geographical Review article (Higbee, 1947), this area, labeled the "Pacific Coastal Plain" in that article, had very fertile land, "favored by a warm climate and a rainy season lasting from May to December; two crops of corn, each averaging between 25 and 70 bushels to a hectare, can be grown in succession on a single piece of land each year.” Beans and rice were grown here because they mature quickly. Sugar cane was grown in this region as well. Further, in 1947 there was an 8700-hectare Tiquisate banana plantation of the United Fruit Company that was approximately 80 kilometers from the study area. In order to counteract the effect of the low rainfall during the annual dry season, the banana plantation was irrigated. Cattle, also raised in this area, were called “ganado Cimarron” or "wild cattle;" the cattle would roam for grazing because the forest and brush were not sufficient for rotational grazing.

In 1983, according to the CIA, much of the same land-uses were active (Figure 2.3). Cotton cultivation, which had accompanied food farming, was suspended in large part in 1980 due to cotton blight; afterward, many of the cotton farms were converted to pasture for cattle grazing (Vidgen and Schechter 2010).

Present Land-Use

Palm and banana monoculture plantations began to expand at the near the close of the 20th century and the beginning of the 21st century (Wolfgang Krenmahr, personal communication, 2012, World Rainforest Movement, 2012). Prior to that time, there were both types of plantations in this area, but at a much smaller scale.

There are still some cattle operations in areas near the wetlands where the soil is not as fertile due, in large measure, to an increase of clay content. Many of the grazing areas have been converted to the palm plantations. In addition to those plantations and the banana plantations, current land-use includes the non-plantation agriculture of subsistence farming, primarily maize and beans (Figure 2.3).

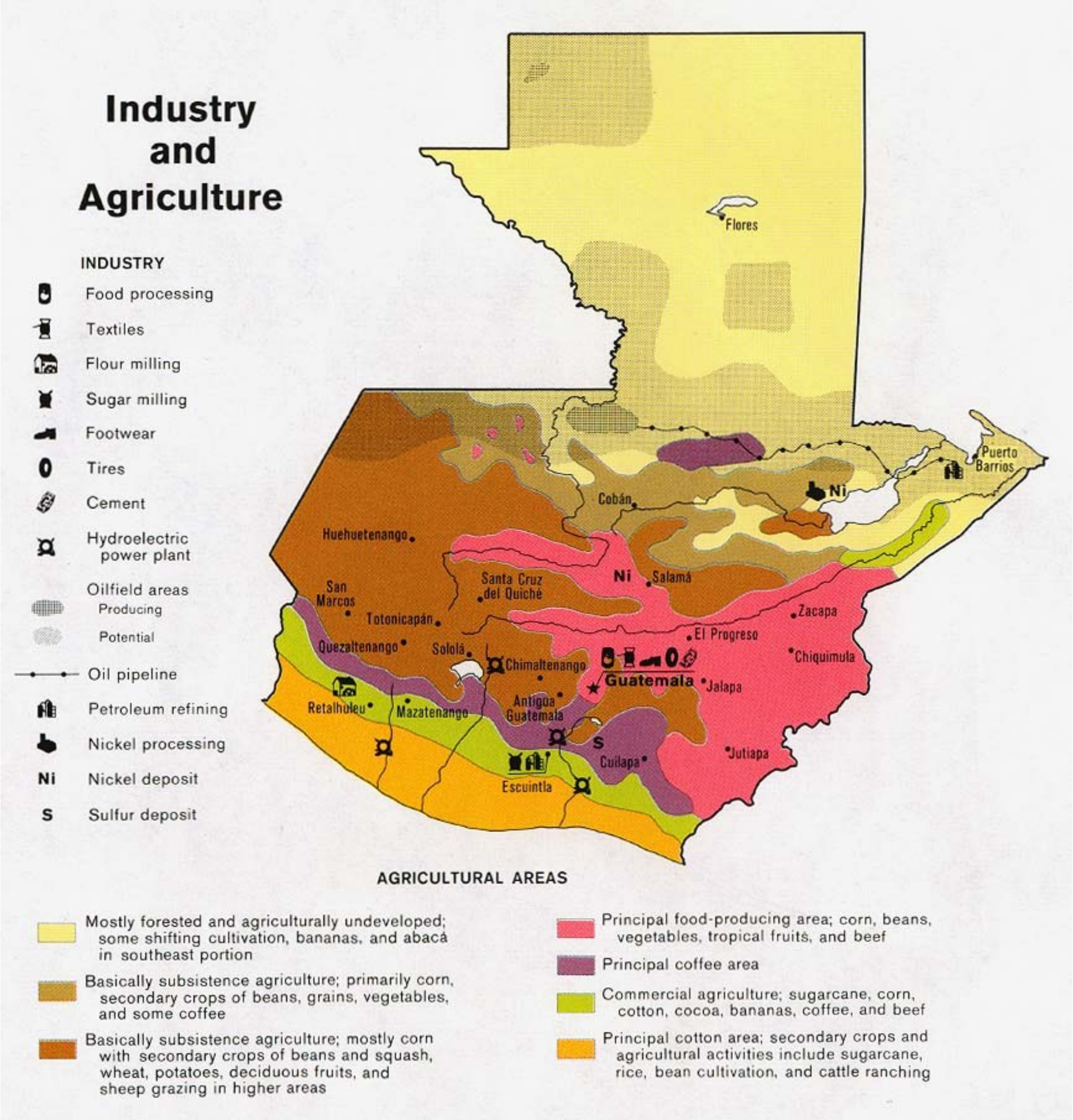


Figure 2.3. Map of industry and agricultural areas of Guatemala (Mapa Munda; CIA, 1983).

In recent years, peasant communities surrounding these plantations have experienced massive flooding that they attribute to environmental changes introduced at the beginning of the 21st century by banana and palm oil plantations (Wolfgang Rehmad, personal communication, 2012). These African Palm (*Elaeis guineensis jacq.)* and banana plantations diverted a river from its natural course to water the plants, increased the elevation of the river banks, and eradicated multiple wetlands areas. The African Palm plantations were introduced in the 1990s, and a significant numbers of plantations have been added since 2000. According to Tuinstra (2008), African Palm requires certain growing conditions and climatic conditions, such as:

- a maximum average temperature of 29°C and minimum average of 22-24°C
- continual sunshine or 5 hours/day for each day of the year
- greater than 75% relative humidity
- rainfall greater than or equal to 2000 mm throughout the year
- loam or clay-loam soils with good permeability and drainage.

Production of palm oil has been blamed for ecological problems, including deforestation, loss of biodiversity or wildlife species, destruction of habitat (both for people and animals and wildlife), soil, air, and water pollution, and toxic chemical contamination (World Wildlife Fund, 2012). Unlike Indonesia and Malaysia, where forests were cleared to plant palm, in this area wetlands have been removed and river courses changed to enable better irrigation during the dry season, as well as to increase water drainage during the wet season.

The increase in land conversion to palm plantations also impacts water quality. Palm-oil processing utilizes large quantities of water in the extraction of the oil from the palm fruits. During this extraction of crude palm oil from the fruit, about 50% of the water becomes contaminated and is referred to as “palm-oil-mill effluent (POME).” It is estimated that for each metric ton of crude palm oil produced, 5.0 -7.5 metric tons of water becomes POME (Okwate and Isu, 2007). Direct release of this effluent into streams and waterways can cause freshwater pollution, which can affect downstream biodiversity and people who drink the water.

It should be noted that palm-oil production requires less fertilizer per unit of output than other oil-seed crops. Nutrients such as nitrogen, phosphorus, and potassium are applied regularly to oil palm trees, particularly if soil conditions are not optimal (Tuinstra, 2008). The primary pesticide used on palm plantations is poison to control rats.

Banana plants require frequent and intense applications of fertilizer and pesticides. Growing conditions of these plants need between 25 and 50 mm of water per week, depending on evapotranspiration rates (Castillo, 2009; Henriques, 1997). Soils must also have high nutrient content to maintain proper yields or rely heavily on fertilization containing high levels of nitrogen, potassium, and phosphorous. High precipitation and the vulnerability of the monoculture crop to disease and pests result in large quantities of pesticides being applied (Castillo, 2000).

As noted above, there is evidence of horticultural adaptation by the Mayans in the study area (vicinity of Manchon) between 1000 and 1500 BC (Beach, 2006; Neff et al., 2006), and evidence of even earlier human activity has been found in the general area of the Ramsar wetlands. Further, shifting horticulture was an agricultural practice exercised by Mayan farmers in the deciduous tropical forest. The more recent inhabitants have grown corn, beans, and cotton, and raised cattle (Figure 2.3). A sharp decline in cotton cultivation began about 30 years ago and production was essentially terminated by 1995 (Index Mundi, 2012) due to a cotton blight; afterwards, many of the cotton farms converted to cattle ranching. In general present-day agriculture in the area consists of subsistence farming, primarily maize, and beans, and plantation farming of African Palm trees and bananas (Figure 2.4).

Geologic Framework

Tectonic Plates

Geologically, Guatemala is largely characterized by volcanoes and earthquakes. These result from its setting in regard to the configuration and movement of plates of the earth’s crust. In the general region (Figures 2.5 through 2.7) are:

- Caribbean plate to the east: its western part is southern Guatemala.

- Northern American plate to the north: its southernmost part lies in central and northern Guatemala.
- Cocos plate to the west: its northwestern margin is defined by the Middle America trench.

Much of the earth's instability expressed by geologic activities in Guatemala reflects the relative movement between the plates, especially the Cocos plate, as it is being subducted under Central America and southern Mexico (the Caribbean and North American plates). On a larger scale, the South American plate seemingly has moved more westerly than those parts of the Western Hemisphere immediately to the north and south of it, possibly resulting in the formation of smaller plates (i.e., Caribbean, Cocos).

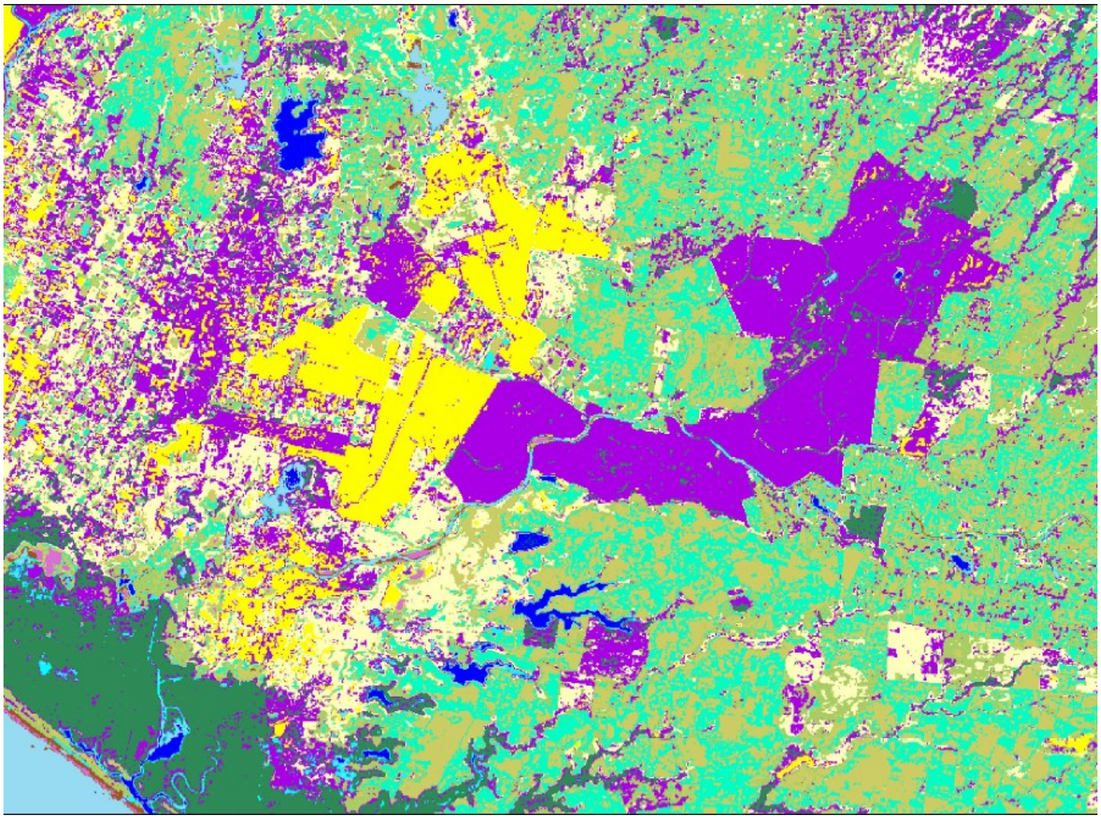


Figure 2.4. Current land-use map of study area, based on analysis of remote-sensing data. The main types of use are categorized as follows: oil palm plantations (uniformly purple), banana plantations (uniformly yellow), wetlands (uniformly dark green), and farmlands (well drained [light green to turquoise, purple] and marginal wetlands [salmon to mottled]).

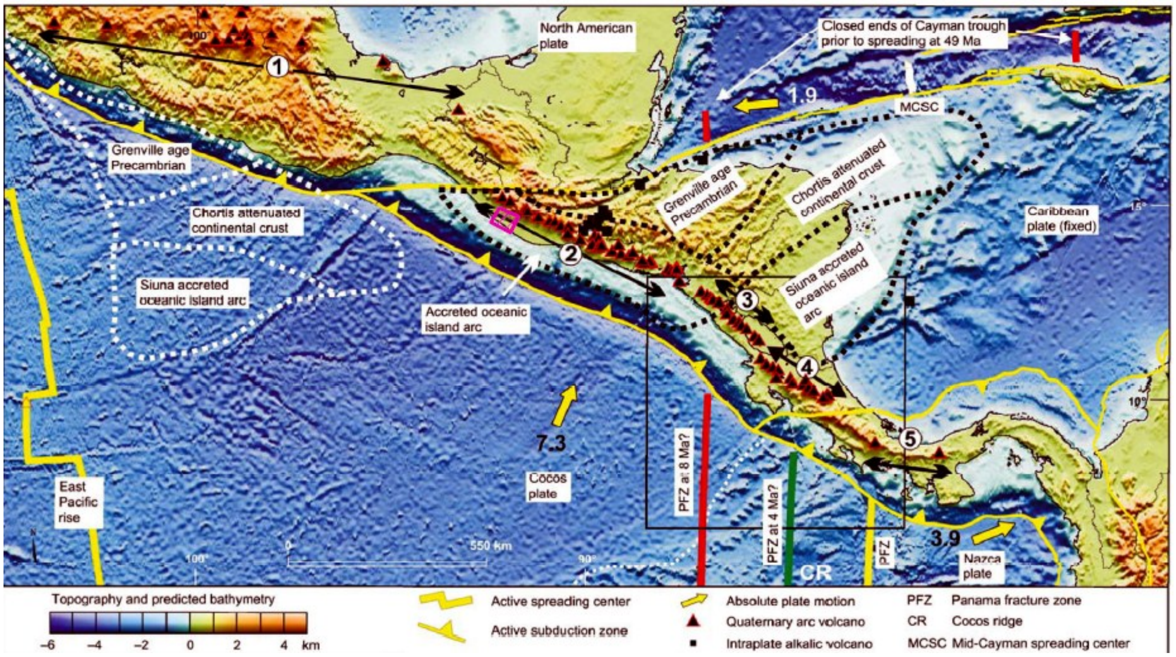


Figure 2.5. Tectonic plate map of Central America, showing locations of Caribbean, Cocos, Nazca, and North American plates. Guatemala is the area where the Caribbean, Cocos and North American plates intersect or converge. The encircled number 2 (with arrows to the northwest and southeast) is located at the southeasternmost point along the Guatemalan Pacific coast. (From Mann et al., 2006). Study area highlighted as pink square.

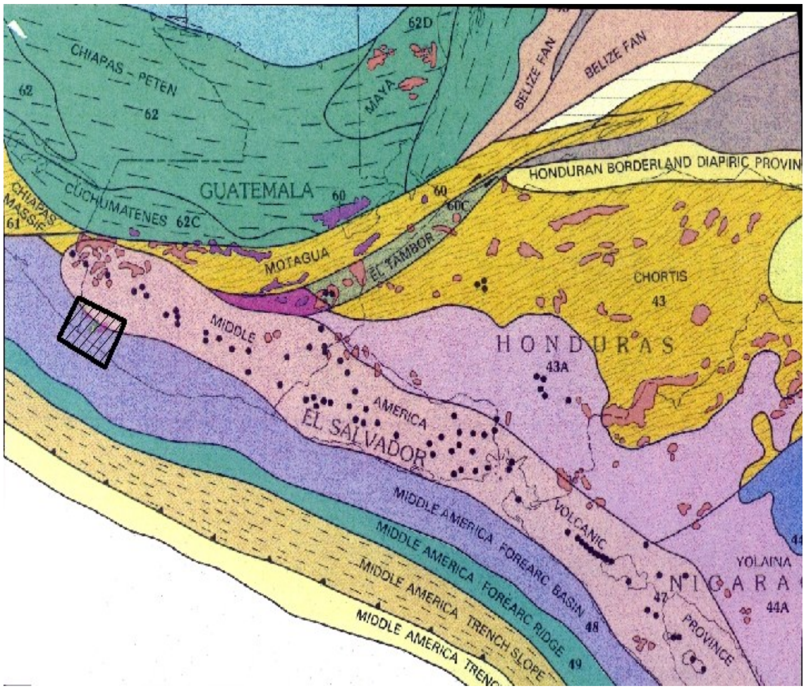


Figure 2.6. Tectonic provinces of Central America within the different tectonic plates. Maya block in the north and Chortis block to the southeast are separated by the Motagua zone (From Case et al., 1984). Study area is designated by black hatch pattern.

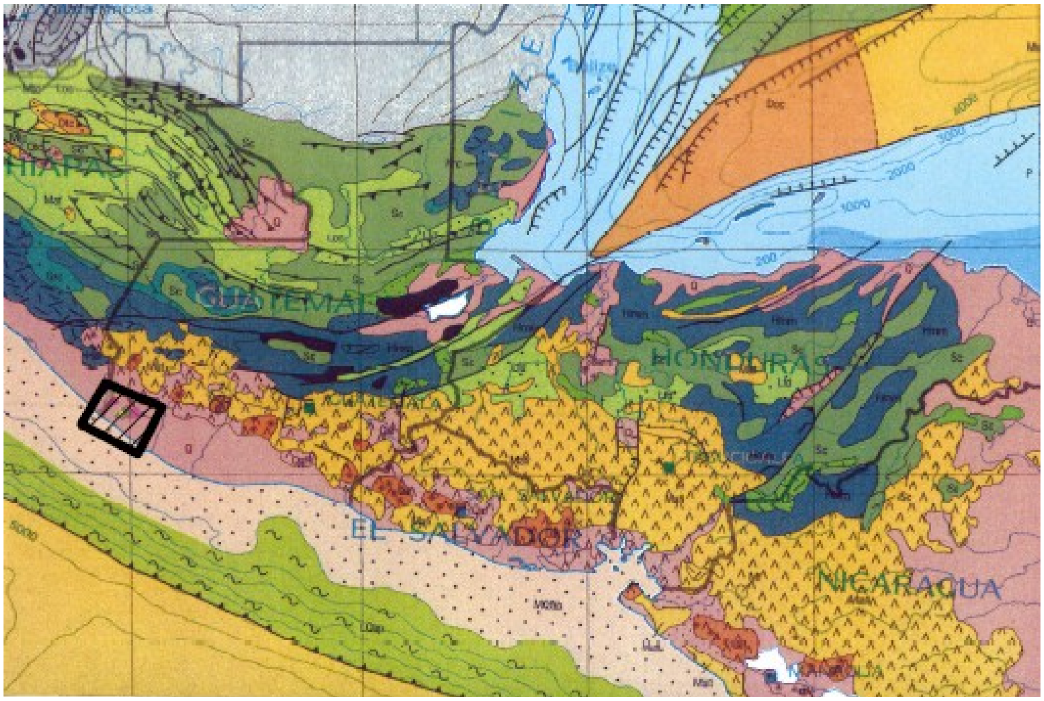


Figure 2.7. Tectonic map of Central American, with tectonic plates defined by fault zones and with northwest-trending belt of Cenozoic volcanics (shown by inverted V's) and narrow belt of Quaternary sediments (Q) to the southwest of the volcanics and extending to the northwest into Mexico beyond the volcanic belt (from Muehlberger, 1992, 1996). Study area highlighted as black hatch pattern.

Provinces/Zones/Blocks

In Guatemala, the North American plate is defined on the south by: a major fault zone, a transform boundary, across which the North American plate has moved some 130 kilometers to the west relative to Caribbean plate (Figure 2.8; Burkart, 1978), with predominant movement in the Neogene (25-2 million years ago). Within in this fault zone (Motagua), three major faults have been recognized: Polochic, Motagua, and Chamelecón (Case et al., 1990). On outcrop in this zone is a wide range of rock types, representing also a wide range of ages (Precambrian to Cenozoic) in a disorderly fashion and "floored" mainly of continental crust but with at least one block of oceanic crust (Burkart, 1978; Case et al., 1990).

The Mayan block to the north of the Motagua zone is a relatively stable continental-crust block as part of the North American plate. In the west are questionably Precambrian and Paleozoic igneous and metamorphic rocks and to their north and east are major belts of folded strata, which in turn are bordered to their east by less deformed rock sequences, including the Yucatan platform (Case et al., 1990; Donnelly et al., 1990). This area, with relative lowlands and karst topography, is in sharp contrast to the rugged terrain of the central cordillera (of Paleozoic metamorphic rocks) and the Cenozoic volcanic belt to the south.

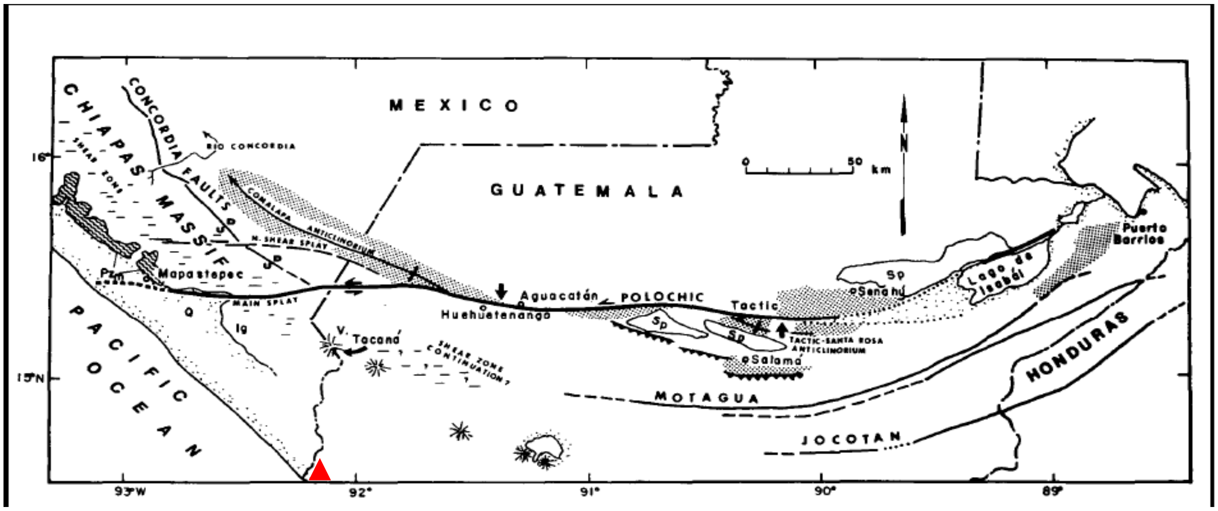


Figure 2.8. Map of western Guatemala and southern Chiapas, showing the Polochic fault, the northernmost major fault of the Motagua zone, which separates the North American plate from the Caribbean plate (from Burkart, 1978). Red triangle indicates study area.

Volcanism

The volcanic front of Central America extends from the Guatemala-Mexico boundary to central Costa Rica, more than 1000 kilometers in length, and terminates abruptly at both ends. The northwestern end is near the Caribbean-North American plate boundary, as well as near the intersection of the Pacific coastline and Guatemala-Mexico boundary. Forty major volcanic centers have been recognized along this front, with 21 in Guatemala, including Tacaná, Santa

María, Atitlán, Fuego, and Pacayá (Carr and Stoiber, 1990) (Figures 2.9 and 2.10). Several centers in Guatemala trend northerly to northeasterly. Basalt and andesite are more abundant than silicic tephra, although much of the silicic volcanism is from Guatemala volcanoes, especially the Atitlán caldera. Basaltic cinder cones and shield volcanoes, although much less impressive than the composite stratovolcanoes, are common in southeast Guatemala.

Measurements of volcanic gas have included analyses of sulphur (S) and chlorine (Cl) contents of the basaltic magma that erupted at Fuego in 1974; S was 2800 ppm, and Cl was 800 ppm (Rose et al., 1978; Rose et al., 1982). An ash blanket of 0.2 km^3 was produced at Fuego in 1974, when eruption included nueés ardentes (Davies et al., 1978).

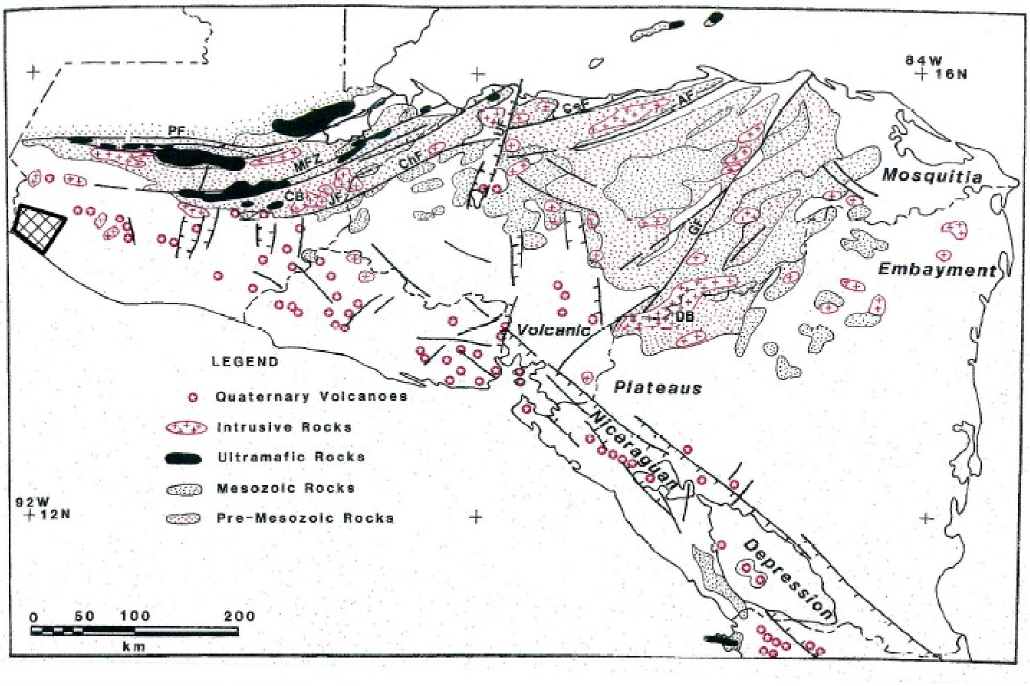


Figure 2.9. Quaternary volcanoes in Central America. In Guatemala the most recent prominent volcanoes generally are aligned along and nearest the coast (from Donnelly et al., 1990), Study area is represented by black hatch pattern.

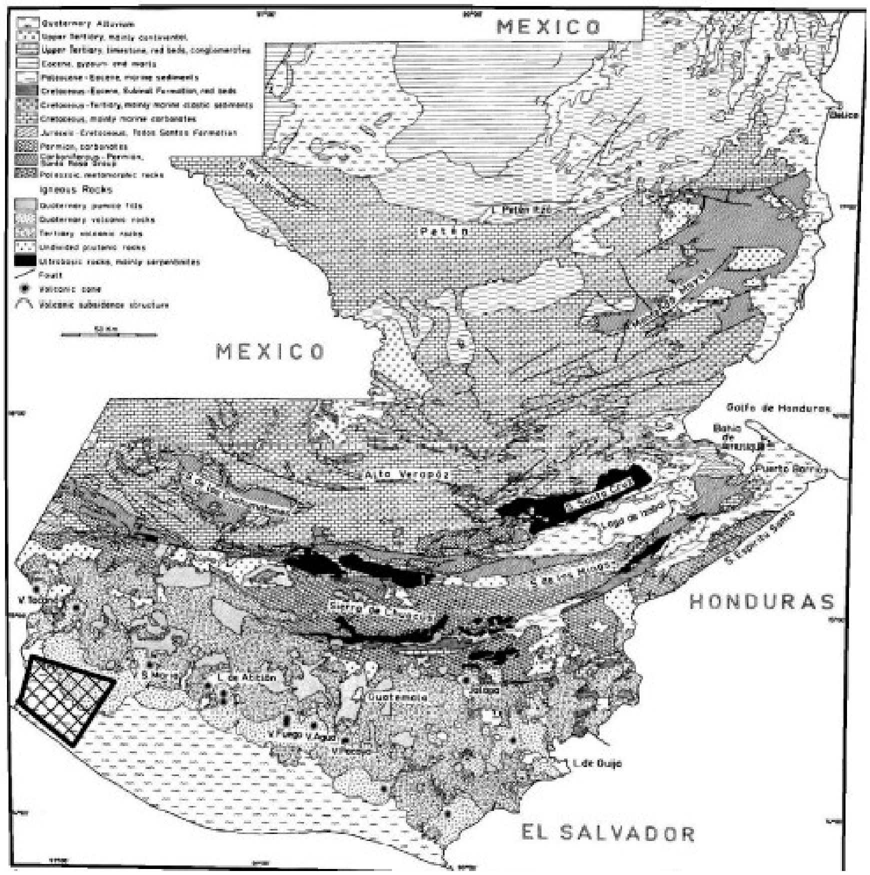


Figure 2.10. Geologic map of Guatemala (from Weyl, 1980, Fosdick et al., 2005). Study area is represented by black hatch pattern.

Earthquakes

The subduction zone, expressed as the Middle America trench and located some 50 kilometers off the Pacific Coast of Guatemala, led to the formation of the Central America volcanic front, or arc. Both the arc and the trench are belts of earthquake activity, and in Central America volcanic eruptions and major shallow earthquakes are related in time and space (Carr and Stoiber, 1990). Santa María in 1902, the largest historic eruption, followed the largest recorded shallow earthquake in Central America by three months. Intermediate-depth earthquakes have shown clustering (Carr, 1984). The highest levels of that type of activity in 1963-1980 occurred in the vicinities of the then active Santa María, Fuego, and Pacayá volcanoes. Clusters of small shallow earthquakes occur beneath active volcanoes. Usually the destructive earthquakes in the volcanic belt are not connected directly with volcanic activity.

The Middle America trench, an important source of offshore earthquakes, and the Motagua zone are the other major sources of earthquakes. The most destructive earthquake in recent Guatemalan history was along the Motagua fault in 1976. The magnitude was 7.5 (on the Richter scale), and the focus (depth) was 5 kilometers; this shallow earthquake resulted in 23,000 deaths. The 1942 earthquake near the coastline in southeast Guatemala had a magnitude of 7.9; its focus was 60 km, reflecting its association with the Middle America trench. Its destruction was widespread but less than the 1976 earthquake; the death toll was 38. As recently as September 20, 2011, there were four earthquakes in southeast Guatemala in the Santa Rosa area, with the maximum magnitude of 5.8.

Pacific Coastal/Alluvial Plain

South and southwest of the belt of Cenozoic volcanic rocks lies the coastal plain adjoining the Pacific Ocean (Figure 2.10 and Figure 2.11). Actually it is largely a Quaternary alluvial plain, with most streams flowing in restricted sinuous patterns to the ocean. The area, adjacent to mountainous terrain, represents, to a large extent, the coalescence of alluvial fans to form a distributive alluvial plain. The overall gradient of the plain is less than 10 meters/ kilometer (from Retalhuleu to the coast). The shoreline is relatively straight indicating wave action sufficiently strong to counteract, in general, the stream input to the coast. In detail lagoons and estuaries are present at the mouths of a number of rivers. It appears that some of the coastline may have been quite irregular prior and during the initial stages of rising sea level at the end of the last stage of glaciation. As the coastal processes straightened the shoreline, the lagoons and estuaries formed, and their vestiges remain as coastal wetlands.

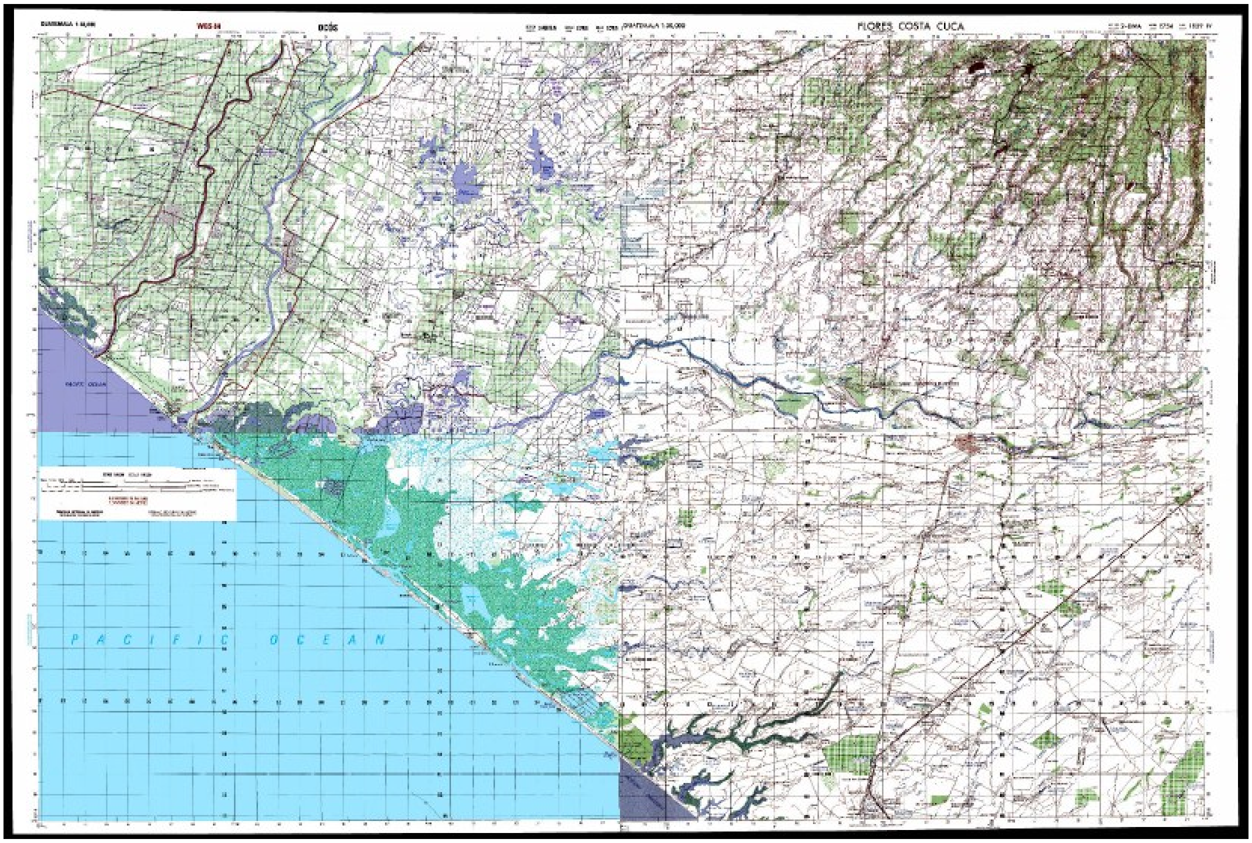


Figure 2.11. Composite topographic map of study area. Map is derived from parts of "quadrangle" maps (Manchon, Ocos, Flores Costa Cuca and Champerico), prepared by U. S. National Imagery and Mapping Agency, Series E754, with the cooperation of the Instituto Geografico Nacional (IGN) Guatemala, 1978, 1993, 1995.

Hazards

Guatemala, by virtue of its position with respect to tectonic plate movement, has a wide range of hazards directly related to its geologic setting. In addition, other physical hazards relate to a combination of climate/weather and its geologic setting. Physical hazards include:

- Earthquakes—damage from the earth's movement and ancillary damage (e.g., mass movement [landslides, mudflows], fire)
- Volcanic eruptions—lava flows covering landscape; nueés ardentes, ash blanket, mass movement, fire
- Floods—water damage and subsequent mass movement
- Tsunamis—water damage and subsequent mass movement

- Hurricanes/tropical storms—water and wind damage, subsequent mass movement
- Tornadoes—wind and water damage; subsequent mass movement

Undoubtedly the hazards that are presented to Guatemala represent risks as great as almost any country of comparable size. Some of the expected or extrapolated damage can be mitigated by human planning and preventive/precautionary action.

Key Geologic Features and Physiography

The general area of study lies in the Pacific coastal/alluvial plain with unconsolidated Quaternary sediments at the surface. These sediments, derived from the volcanic highlands to the north and northeast, were deposited predominantly by streams flowing toward the Pacific Ocean to form a seaward-sloping alluvial plain. Rio Suchiate on the west and Rio Samala on the east show that orientation. Rio Naranjo immediately to the west of the study area, in its lower reaches, is also oriented normal to the shoreline (Figure 2.11), whereas upstream it shows a stretch in which it is oriented subparallel to the shoreline and to the faults of the Motagua zone. However, in the immediate the area of study, the Ocosito and the smaller Rio Pacayá show more sinuous courses; both are distributive-type of streams, by bifurcating upstream from entry into the ocean. Also, both show features of meandering-braided streams (braided during low-water stage within a meandering course).

Rio Pacayá , in its downstream section, not only contains distributaries, but it also show abandoned stretches and abandoned meanders (Figure 2.11 and Figure 2.12). Some interfluvial areas contain lakes of varying sizes. These rivers flow westerly over considerable parts of their lengths, parallel to trend of the faults of the Motagua zone. Flow in the lower reaches of the two rivers is more southwesterly, as each becomes less prominent due to the bifurcation inland from the coast. The Orocito empties into a lagoon, with a nearby tidal inlet. The Pacayá, especially, becomes noticeably less prominent downstream, where it is referred to as a zaranjo (gully or ditch), as it also empties into a lagoon. The coast has estuaries as well as lagoons behind long but narrow barriers. The coastal processes on this plain are restricted to a narrow zone adjoining the ocean, except in times of hurricanes and tropical storms. Stream-related processes in interfluvial (floodplain) areas, such as overbanks and backswamps, deposited finer grained sediments, along with a higher content of organic matter, than the stream deposits. Fluvial deposition continues as the streams, which are rather closely spaced, shift laterally. North of the Ocosito, the overall slope of the surface is generally 7.5-15 meters/kilometer. Near the coast, south of the Ocosito where it flows more westerly, the slope is less than 1 meter/kilometer.

Susceptibility to weathering in a tropical climate is a function of the original composition of the sediments at the time of deposition, but also of the organic material, both living and dead, and drainage. With time, the role of climate becomes dominant in most cases, but drainage is also important (Dosseto et al., 2006).

North of the study area in the upper reaches of the coastal/alluvial plain, the sediments contain clastics from andesitic to basaltic flows and pyroclastics (volcanic breccias, tuffs, ashes, and volcanic mudflows [lahars]) (Ambiene y Desarrollo, 2011). Downslope the material is finer grained (e.g., average 0.5 mm in diameter, with lapilli pebbles) and angular to subangular in terms of roundness, and alluvial (stream) features dominate the internal character of the deposits, which are at least tens of meters thick. In some parts they may be substantially thicker due to structurally controlled subsidence during deposition. Sediment colors are red, brown, gray, and beige.

Figure 2.12. Low-angle perspective image of study area from Google Earth, showing stream patterns, coastal features, and colors of vegetation and soil.

Soils

The soils in this area are derived from volcanic materials, including ash as well as flows, are young, deep, and fertile. At the surface, the soil is commonly clay to silt loam. This topsoil is slightly acidic, dark in color, and 30 to 50 cm thick. The subsoils are commonly clayey loam, slightly acid, and yellowish-to-reddish brown; they are of varying depth, from one to two meters. In the classification by Simmons et al. (1959) as shown in Figure 2.13, the soils predominantly belong to the Ixtán series (Ix). They occur on flat surfaces with slow drainage; they have high fertility. However, they are susceptible to erosion, and other issues are drought management and maintenance of organic matter. Representative soil sampling sites in the nearby Retalhuleu area and reported in Ambiene y Desarrollo (2011), have the following features:

Physiography: Terrace

Elevation: 9 meters

Slope: Very gentle (less than 1%)

Drainage: Poor, subject to flooding

Land-use: Oil palm plantation (for 2 years)

Texture: Cobble free

Source material: Alluvial deposits, derived from volcanic materials

Effective depth: More than 90 cm

Rate of erosion: No evidence of erosion

Site	Soil Horizon	Depth	Description
1	A	0-35 cm	Pale brown dry and very dark grayish brown wet silt loam, granular, friable, not plastic, few medium and fine roots, wavy boundary, 32 to 38 cm thick.
1	A2	35-45 cm	Color brown dry and very dark brown moist, silt loam; granular, friable, not plastic, few roots, wavy contact, 43 to 48 cm thick
1	AB	45-80 cm	Color dark brown dry and very dark brown wet, silt loam, granular, friable, not plastic
2	A	0-19 cm	Color brown dry and very dark brown moist, fine granular, friable, not plastic, few medium and fine roots, wavy contact, 17-22 cm thick.
2	A2	19-50 cm	Color brown dry and very dark brown moist, fine sandy loam, fine granular, friable, not plastic, medium and fine roots few, sharp lower contact.
2	A3	50-70 cm	Color yellowish brown dry and dark brown moist, sandy loam, fine granular, non-adherent, not plastic, friable, scarce roots, sharp contact.
2	AB	70-90 cm	Color dark yellowish brown dry and dark brown wet, fine sand, friable, not plastic, no roots.

(Wilfredo Díaz Lima, in Ambiene y Desarrollo, 2011)

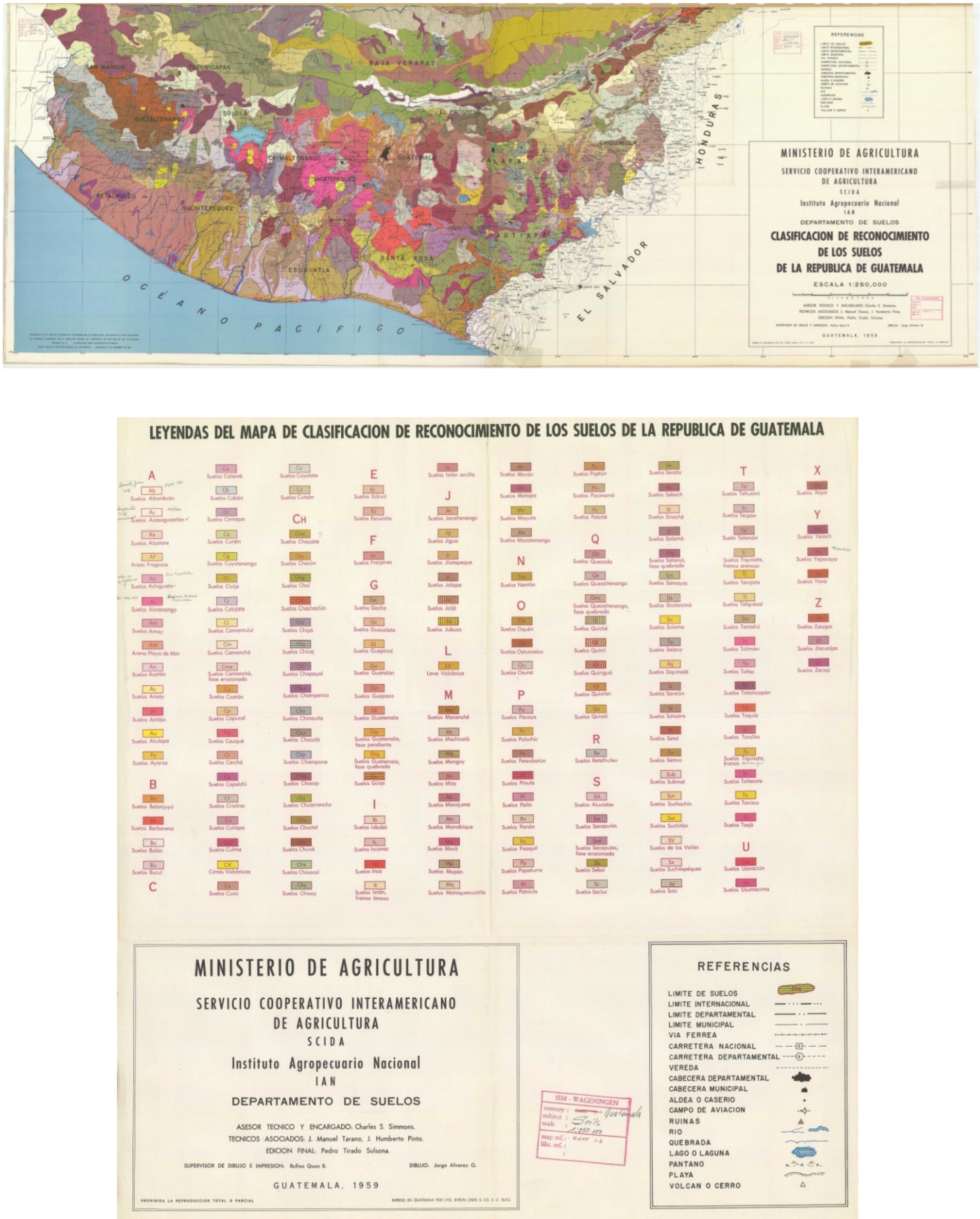


Figure 2.13. Soil map, with separate legend, of the Pacific coastal plain and alluvial plain south and southwest of the volcanic-mountain terrain (in Spanish) (Simmons et al., 1959).

Utility of Soils

In the area studied as part of the Minerva Project (Ambiene y Desarrollo (2011), the soils are deep; highly fertile; the topography is flat and easily worked by machinery, and these soils require little management practices and soil conservation. The other 50%, which have flooding as a concern/hazard, are also deep soils with flat relief. They are loamy sandy silt loam and clay loam; they are highly fertile and easily worked by machinery, and they require few management practices and soil conservation. However, they present the problem of flooding during the rainy season due to overflowing rivers.

Hydrology

Surface Water

The flow characteristics of the Orocito River approximately 15 kilometers upstream from the study area (at Caballo Blanco) are considered to be generally representative of streams in the region (Ambiene y Desarrollo, 2011). Between 1969 and 2010, the highest average annual flow was 43m^3/sec in 2005-2006, reflecting Hurricane Stan. The year with lowest mean annual flow recorded is 2001-2002, with 20m^3/sec. The average annual flow of the Ocosito River for the decade 2000-2009 is 30m^3/sec, which is essentially the same as average annual flow for the total duration of data collection (31m^3/sec).

The Ocosito has had the lowest monthly average in March, with 5.4m^3/sec as the record low, while the record daily low flow is 5m^3/sec. The peak flow (during September) is 75m^3/sec, declining to 27.5 m^3/sec in November. At the start of the dry months (in January) the flow rate is 8m^3/sec, with March as the month of lowest flow. This dry period is critical for water supply using irrigation, as a vital part of the agricultural strategy. Maximum daily flow rates are approximately

$330m^3$/sec to slightly more than $350m^3$/sec (both in September). The lowest rates have ranged from slightly more than $1m^3$/sec to slightly less than $2m^3$/sec (in March and April).

Because the area is located on an alluvial plain where deposition is dominant, large-scale, long-term erosion is not a problem. However, local erosion along the rivers during flooding is a risk, and flooding itself is a risk in the floodplain and low-lying areas near the coast. According to Ambiene y Desarrollo (2011), flooding is more likely to occur south of the Minerva project in the lower reaches of the rivers and in the main part of the study area.

Hydrogeology: Groundwater

Because the area consists of alluvium, with some volcanic debris that was deposited from suspension or by mudflows (especially in the northern part and at depths greater than 20 meters), there is generally good storage as well as good vertical and lateral movement of water through the resulting porous, permeable medium—to form an unconfined aquifer. The water table fluctuates with the season, rising during the rainy season and lowering during the dry season (to as low as 10 meters). The aquifer shows heterogeneity and anisotropy, reflecting the variability of sediments deposited by streams in and along their channels and in overbank settings. The grain size shows three-dimensional gradation from gravel, sand, silt, to clay. The general movement of the groundwater is from northeast to southwest, in the same direction as the slope of the water table, as well as the topographic slope and the surface drainage.

It should be noted that clay, deposited in floodplain (overbank) areas, may form significant low-permeable deposits. Also some units contain carbonate, generally cement that probably formed during dry seasons. Because the dark, ferromagnesium minerals are common, weathering associated with soil development and post-depositional changes with groundwater movement are closely associated. The most obvious result is the red soil.

Hydrogeological characteristics of aquifers, transmissivity, hydraulic conductivity and storage coefficient, and infiltration capacity, as determined by Ambiene y Desarrollo (2011), are considered to be typical for aquifers composed mainly of sand and gravel, with an average porosity of 27%. For example the infiltration capacity in floodplain soils measured by Ambiene y Desarrollo (2011) was approximately 60 mm/day.

Conclusions

Guatemala ranks in the upper five countries in the world most affected by floods, hurricanes and earthquakes, with 40 percent of the population exposed to five or more threats simultaneously (World Bank, 2011). There is exposure to high-impact, but low-frequency events, such as hurricanes, earthquakes, and volcanoes. Also, there is vulnerability to low-impact, high-frequency events, such as landslides, and flooding. The characteristics of geology, soils, hydrology, and hydrogeology of this area in Guatemala underlie this vulnerability.

Chapter 3: Measuring Land-Use Change Utilizing Remotely Derived Vegetation Indices

Introduction

The value and use of remotely derived vegetation indices in assessing land-use change are herein described from a contextual perspective as background for the description of the methods used in this study and its results. Included are definitions and an explanation of reasons for the use of this tool, as well as its relationship to field analyses. These items precede the description of specific methods, analyses, and results of this study.

The fundamental question of this research is whether remotely derived vegetation indices provide an accurate estimate of parameters that define land-use values and measure land productivity changes in the tropical setting of northwestern Guatemalan coastal plain. Temporal analysis of remotely sensed images has been used to measure agricultural intensification in Central and South America (Southworth and Tucker 2001, Chowdhury 2006, Chambers et al 2007). Anecdotal evidence suggests that significant land-use changes have occurred is this region in the last 20 years – from wetlands and small farms to palm and banana plantations. If the question is answered in the affirmative, the follow-up question is whether plant growth and productivity, as measured by vegetation indices, on their own, can provide a satisfactory estimate of how this land is losing its resilience. The result would decrease the inhabitants' ability to provide for their own food and increase their vulnerability to climate change. It is critical for human development that land-use activities not impact adjacent lands and their productive capacities. With both questions answered positively, the methods and results of this study may well serve as an analog or case study for future studies in a comparable geographic setting. On the other hand, if the answer to the fundamental question is negative, on-site detailed examination, in significant detail, is required for both landscape and local studies.

Land-Use, Land-Cover Change

Land-use activities, such as clearing tropical forests, practicing subsistence agriculture, intensifying farmland production, or expanding urban centers – all human actions, are changing the world's landscapes in significant ways (Hartter and Southworth 2009). Agriculture is the major driver of land-cover change in tropical regions (Lambin et al. 2001).

Land-cover is the type of physical surface present at a given point on the earth (e.g., forest, grasslands, urban/industrial, lakes/reservoirs/streams). Land-cover is either inherited from the ecosystem or is derived as a result of human activity; the two contrast quite sharply (Mertens and Lambin 1997, Mertens and Lambin 2000, Lambin et al. 2001). Intensive human-derived changes tend to push ecosystems beyond thresholds of resiliency so that the ecosystem becomes 'novel' to its environment and less resilient in a changing climate scenario (Vogt et al. 2010a).

Changes in agricultural practices and their intensity (e.g., irrigation) may increase desertification risk (Geist and Lambin 2004) or decrease soil health (Vogt et al. 2010a). All land-uses involve trade-offs. For example, application of fertilizers to agricultural lands formerly covered by forests can increase the benefits to society when the quantity of ecosystem goods (e.g., food, fuel) increases. However, there are costs if soil health decreases, ultimately reducing ecosystem services and the productive capacity of the soil.

The impacts of land-use change in terms of space, time, and scale are complex. Also, in most cases, there is not a reference site (an analog) to which an ecosystem can be compared in order to identify the causality of the observed change(s). Millennium Ecosystem Assessment (MEA) (2005) identified land-use change as the most significant impact occurring in many developing countries, and that it is increasing the vulnerability of rural communities to climate change. Patterns of land-cover change in most tropical, developing countries are closely linked to land-use changes that are driven by anthropogenic forces, with the change(s) occurring both spatially and temporally and varying in intensity and extent (Nagendra et al. 2003, Wood and Skole 1998, Geist and Lambin 2004). Tropical deforestation, agricultural intensification, and other land-use changes are the result of many actions, both local and regional in scale; teasing apart these drivers of change is critical so that mitigation and restoration can be effectively implemented. DeFries et al. (2004), shows trade-offs by focusing on biodiversity, water quality, soil quality, and climate regulation (key parameters affected by land-use changes). However, understanding the full suite of ecosystem consequences requires quantifiable and measurable indicators for each of the ecosystem functions. Much of this information, however, may not be available (MEA 2003).

Issues of Scale

Interactions and processes that occur across different spatial and temporal scales are important in measuring ecosystem responses. Consequently, determining the interrelationships between ecological processes operating at different spatial and temporal scales is a challenge; e.g., measuring the productivity of a landscape and the impacts of land-use change on productivity.

Information collected at small-plot study areas to address regional land-use changes has been challenging because data needs and the amount of required information change with scale (Kok and Velddamp 2001, Vogt et al. 1997). In most cases, analyses of a region may have lower data needs than smaller scale analyses, which also have a higher diversity of parameters that must be monitored.

Although most ecological issues must be addressed at a landscape scale, much of our data comes from local studies that must be extrapolated to the landscape. Erosion and deposition of soil and nutrients by water and wind are examples of spatial processes that influence ecosystem dynamics (Neilson and Running 1996). Ecological scaling and efforts to define widespread patterns are challenged by the inherent nonlinear and divergent interrelationships found in ecosystems.

Appropriate scale and resolution independently are important in measuring changes in ecosystem health (Gardner et al 2001, Chhabra et al. 2006). Care must be taken in the extrapolation of plot-scale data to the landscape, whether it involves field observations or a combination of field observations and remotely-sensed data (Gardner et al. 2001, Turner et al. 1999). Relationships observed at plot-level scales may include important patterns and processes on broader scales, but large-scale observations may not include enough detail to understand the finer scale dynamics.

Use of Remote Sensing

Remote sensing from satellites is often the only economically and logistically feasible way to gather land-cover information with high spatial, spectral, and temporal resolution over large areas. The combination of field data and remote-sensed data provides the ability to analyze smaller geographical areas and create accurate estimates of landscape and forest attributes (Tomppo et al. 2008, Kreuter et al. 2001). Repetitive measurements of spectral, spatial, and temporal indicators of a land surface can be made that accurately monitor land productivity as well as changes in the health and resilience of any land-base.

Field data provides valuable information that cannot be assessed by remote sensing. However, the combination of field data and remote-sensing data provides the ability to analyze smaller geographical areas in order to make assumptions about ecosystem attributes (Reese et al. 2003, Tomppo 2008). Repetitive remote measurements of spectral, spatial, and temporal indicators of a land surface have to be performed to accurately monitor tropical land and forest degradation. Each set of indicators brings a specific type of information on the land-cover, and when analyzed in combination, the data sets can yield a broad description of the surface processes. Inter-annual changes in landscape spatial structure can potentially reveal long-term land-cover changes, while spectral indicators are sensitive to fluctuations in primary productivity (Lambin 1999). In Nepal, the results of innovative forest management practices were located using a temporal analysis of Landsat TM imagery (Schweik 2003). Landsat 7T is considered the workhorse of remote sensing. It is used extensively to measure land-cover change and has been used effectively to estimate forest productivity in homogeneous forests and agricultural lands (Lu 2003, Nemani and Running 1989, Franklin et al 1997).

In the absence of field data, land productivity and vegetative cover can be estimated using satellite data only. Land-cover data from Landsat ETM images has been successfully used to classify vegetation and measure vegetation change, as well as changes in productivity, in all types of ecosystems when research sites are inaccessible (Langner et al. 2007, FAO 2008). Remote sensing can extend information to create a larger understanding of ecological, biochemical, and hydrological processes and to monitor vegetation changes relevant to sustainable resource and land-management practices (Gunlu et al. 2009).

Each set of indicators, e.g., Normalized Difference Vegetation Index (NDVI) and enhanced vegetation index, brings a specific type of information on the land-cover, and when analyzed in combination, these sets can yield a broad description of the surface processes (FAO 2008). Field observations provide very specific stand data, but the integration of plot data with satellite information can provide information that neither type of data can provide alone. Also, satellite data combined with locally derived data can be combined to develop a database, with statistics, that is not possible using plot data alone (Tomppo 1991, Reese et al. 2003).

Remote sensing and GIS have been successfully utilized by the FAO, Global Land Degradation Assessment (GLADA), and Land Degradation Assessment in Drylands (LADA) to measure changes in land quality (FAO 2008). There are no internationally accepted criteria for measuring productivity and land productive capacity or health using remote sensing. Even at the field level, there is a lack of data and broadly acceptable analytical tools for measuring productivity. Remote sensing from satellites is the only economically feasible way to gather information with high spatial, spectral, and temporal resolution over large areas and areas where plot studies are not economically or logistically feasible (Kreuter et al. 2001). However, there are limits because of the relatively short time these satellites have been in operation.

Normalized Difference Vegetation Index (NDVI)

Remotely sensed estimates of productivity are valuable in assessing land productivity or health in areas with little or no data (FAO 2008). Key measurements, such as the NDVI, can allow an inference of ecosystem function that would be difficult to acquire without very detailed ground surveys. The FAO has identified numerous other indicators to detect land quality changes, including: soil erosion, Net Primary Productivity (NPP), and Leaf Area Index (LAI). Yet the most important biophysical indicator of land degradation is vegetative cover measured by NDVI (Fung 2000, Mutanga and Skidmore 2004, Okin and Roberts 2004).

Methods and Materials

To determine if palm and banana plantations in the study area have affected adjacent or nearby natural lands over time, a general description of the methodology and required materials used in this research is provided. The productivity of those lands show changes that can be measured by vegetation indices, especially when a temporal component is included.

Experimental Design

Satellite imagery data was selected to measure the impact of plantations on the productivity of adjacent lands. The data represent both the periods before and after the planting of extensive areas into palm/banana plantations. These data were analyzed for both the dry and wet seasons in order to view productivity changes in the study area over a continuous period of time, i.e., 1997 – 2011. Five agricultural areas (Sites 1-5, Figure 3.1) in different juxtapositions to palm and banana plantations were selected to analyze land-productivity changes over time, using remotely sensed images.

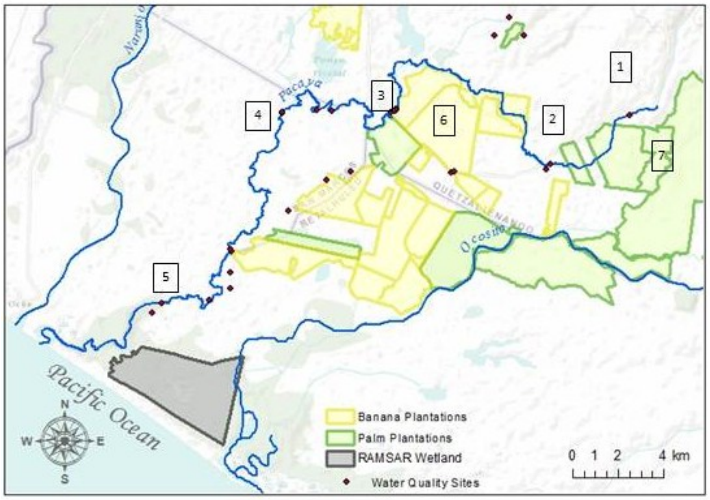


Figure 3.1. Location map of study area with site selections. There are two plantation sites (Sites 6 and 7); the remaining five sites are in the vicinity of the plantations.

Statistical analysis following qualitative analysis was made in order to determine the significance of differences in productivity between sites and between seasons. A permutation test and variability trend analysis were performed because of the non-parametric nature of the data (as described in later sections).

Site Selection

Local agricultural sites along the Pataya River were selected based on proximity to the plantations. These sites are also located in proximity to the water quality survey locations discussed in Chapter 2, and each site has uniform land-use. For example, Site 1 (Figure 3.1, Table 3.1) was selected on the basis of its remoteness to plantations compared to other selected sites and its proximity to water quality data sites. . Because of the local topography, proximity for this research is defined as the distance from a plantation and, more importantly, the difference in elevation between the study site and the plantation (Table 3.1). The banana plantation site (Site 6, Figure 3.1) and a recently converted palm plantation site (Site 7, Figure 3.1) were selected for this study to detect the impact on productivity subsequent to land-use conversion to plantations as well as to measure the productivity of the plantations themselves.

Table 3.1. Characteristics of the Research Sites, Each Selected on Land-Use Uniformity and Proximity to Water Quality Survey Locations

Site	**Elevation Difference From Plantation (m)**	**Distance to Closest Plantation (km)**	**Land-Use Description**	**Basis For Selection**
1	40	2.3	community agriculture	Remote Site for Control
2	10	1.3	community agriculture	Transition to Control Site
3	5	.7	wetland, wetland removal,(by drainage), agriculture	Near Plantation, Wetland Removal
4	0	4.7	community agriculture, flooding issues post plantation period	Flooding Impact
5	-5	5	community agriculture, wetland	Wetland, Farming
6	0	N/A	banana plantation, converted from wetland after 1998	Banana Plantation
7	0	N/A	palm plantation converted after 1998	Palm Plantation

Image Analysis and Preprocessing

The area assessed for this research is defined by Landsat Worldwide Reference System (WRS) as path 21 row 50. The portal of the data is the United States Geological Service's (USGS) Global Visualization Viewer (GLOVIS) website. The data used was from Landsat TM/ETM (Thematic Mapper/Enhanced Thematic Mapper) scenes row 20 path 51 for the dry season and before the increase in the area converted to plantations (years 1998 and 1999), and after the increase (years 2001, 2009, and 2011), and wet seasons (years 1997 and 1999), during the increase (year 2000), and after the increase (years 2008 and 2010). Only image areas that were free of cloud cover were selected for this study. The images were clipped to focus on the area of the study.

A region of interest, a polygon, defined by the coordinates 92.20 W 14.80 N and 91.60 W 14.02 N, was created to analyze images using the ENVI 4.7. All image processing was completed using ENVI 4.7 image processing software. Geometric rectification was completed using a 2000 orthorectified data set using a nearest neighbor re-sampling algorithm. The root mean square error was less than 0.5 pixels (< 15 meters). Radiometric calibration and atmospheric corrections were performed.

Subsequent to rectification, radiometric calibration and atmospheric correction procedures were used to correct for sensor drift and other differences due to variations in the solar angle (Jensen 1996). All images were subjected to radiometric rectification using dark objects to correct for atmospheric conditions (Hall et al. 1991). These calibration procedures are necessary because without such calibration any change detection analysis may evaluate differences at the sensor level instead of changes at the surface of the study area (Jensen 2006).

No images were available from August 2002 to August 2007. Landsat 7 acquisition schedules did not include the subject path and row, and Landsat 5 data could not be collected because of the lack of a direct downlink ground station for this area. For images after May 31, 2003, the Landsat 7 ETM sensor had a failure of the Scan Line Corrector (SLC). Since all Landsat ETM images have had wedge-shaped gaps on both sides of each scene, and scan gaps throughout the scene. Landsat gapfill.sav ENVI user function was used to fill in the gaps of SLC-off Landsat ETM+ data with the closest image. The USGS developed a technique which can be used to fill gaps in one scene with data from another, Landsat scene (Scaramuzza et al. 2004). A linear transformation is applied to the "filling" image to adjust it based on the standard deviation and mean values of each band, of each scene. The two file option, with local statistics, was used to perform the histogram matching between the two files as close to each time collection period as possible.

NDVI

Spectral indices are variables generated by mathematically combining two or more original spectral bands in an image to generate a new variable. A spectral index can then be displayed as a new layer. Vegetation indices are used to estimate the amount of green vegetation. These indices have been developed to understand canopy variables and to serve as the basis for many applications of remote sensing for resource management (Jones and Vaughan 2010). Vegetation indices are related to fractional vegetation cover (*f*APAR); however, they are commonly used to estimate the LAI, a measurement of vegetation cover. The NDVI has been used to monitor vegetation and land productivity (Jones and Vaughan 2010). The NDVI captures photosynthetic activity, and it can be used as a proxy of vegetation productivity and quality. NDVI is computed from the near infrared and red parts of the electromagnetic spectrum, providing a measure of absorption of red light by plant chlorophyll as well as the reflection of infrared radiation by water-filled cells. Vegetation is analyzed with spectral bands in the visible red (Red) and near infrared (NIR). NDVI is calculated as NDVI = (NIR -Red)/(NIR+Red). This index outputs values between -1.0 and 1.0, mostly representing greenness, where any negative values are mainly generated from clouds, water, and snow, and values near zero are mainly generated from rock and bare soil. Very low values of NDVI (0.1 and below) correspond to barren areas of rock, sand, or snow. Moderate values represent shrub and grassland (0.2 to 0.3), while high values indicate temperate and tropical rainforests (0.6 to 0.8) (Earth Observatory, NASA).

A time series analysis of seasonal NDVI is a method to estimate NPP over varying biomass types (Jones and Vaughan 2010). The NDVI and the NPP are often used as indicators of plant productivity (Xu et al 2011, Jones and Vaughan 2010). NDVI and NPP are strongly correlated over many diverse ecosystems, and NDVI can serve as a surrogate for NPP (Wessels et al. 2008, Schloss et al. 1999). NDVI is an index with values that range from -1 to 1 where NPP is a measure of carbon over a given area (i.e. kilogram carbon per metered squared), so the two are not equally comparable. NDVI and NPP data for the time period from 2001 – 2010 was acquired for an approximately 6.5 kilometers by 6.5 kilometers area containing the Guatemala study area (Figure 3.2) in order to illustrate the two different measurements over the same time period.

The NDVI, which is related to the amount of vegetation cover on ground, was computed for the calibrated images. This index ranges from -1 to +1, 1 being highly productive and values close to 0 and negative values represented by sand/rocks, clouds, snow. The NDVI was calculated using ENVI 4.7 image processing software for each date. Each image with NDVI values was transferred to ArcGIS version10 geographical information system software for further analysis. Once in ArcGIS version 10, the site areas were clipped and the NDVI values were determined for each site for each of the 10 satellite images, i.e., five for the wet season, five for the dry season from 1997 to 2011. NDVI mean, standard deviation, maximum and minimum values were calculated for each site for each of the time periods.

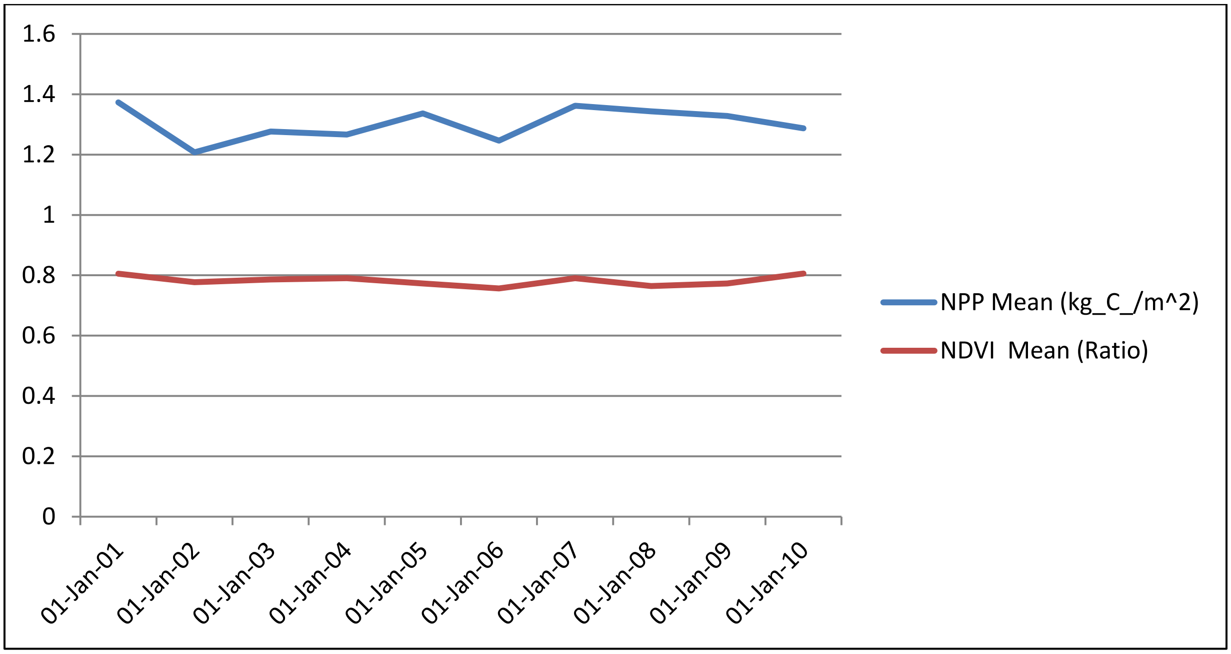


Figure 3.2. Monthly mean NPP and monthly mean NDVI, latitude 14.54915, longitude -92.050598, show a strong correlation so that NDVI may serve as a surrogate for NPP. Source: Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), 2011, MODIS subsetted land products.

Statistical Tests

Values have been analyzed statistically by applying standardized tests, such as calculated means and standard deviations and also by use of permutation test and variability trend analysis (Hesterberg et al. 2003, Ribeiro et al. 2008, Friday 1967). The last two are particularly useful where the data are not abundant and where the nature of the distribution is not known.

Results and Data Analysis

In order to view changes in productivity over a continuous period of time, data before and after the increase in land conversion to plantations was chosen for both the dry and wet seasons.

Per estimates derived from Landsat satellite imagery for the time period (dry season) from 1998 to 2011, the extent of banana plantations increased in area from approximately 660 square kilometers to 940 square kilometers. The areal extent of palm plantations increased from 210 square kilometers to 1,602 square kilometers. These changes in plantation areas (from 1998 to 2011) are shown in Figure 3.3.

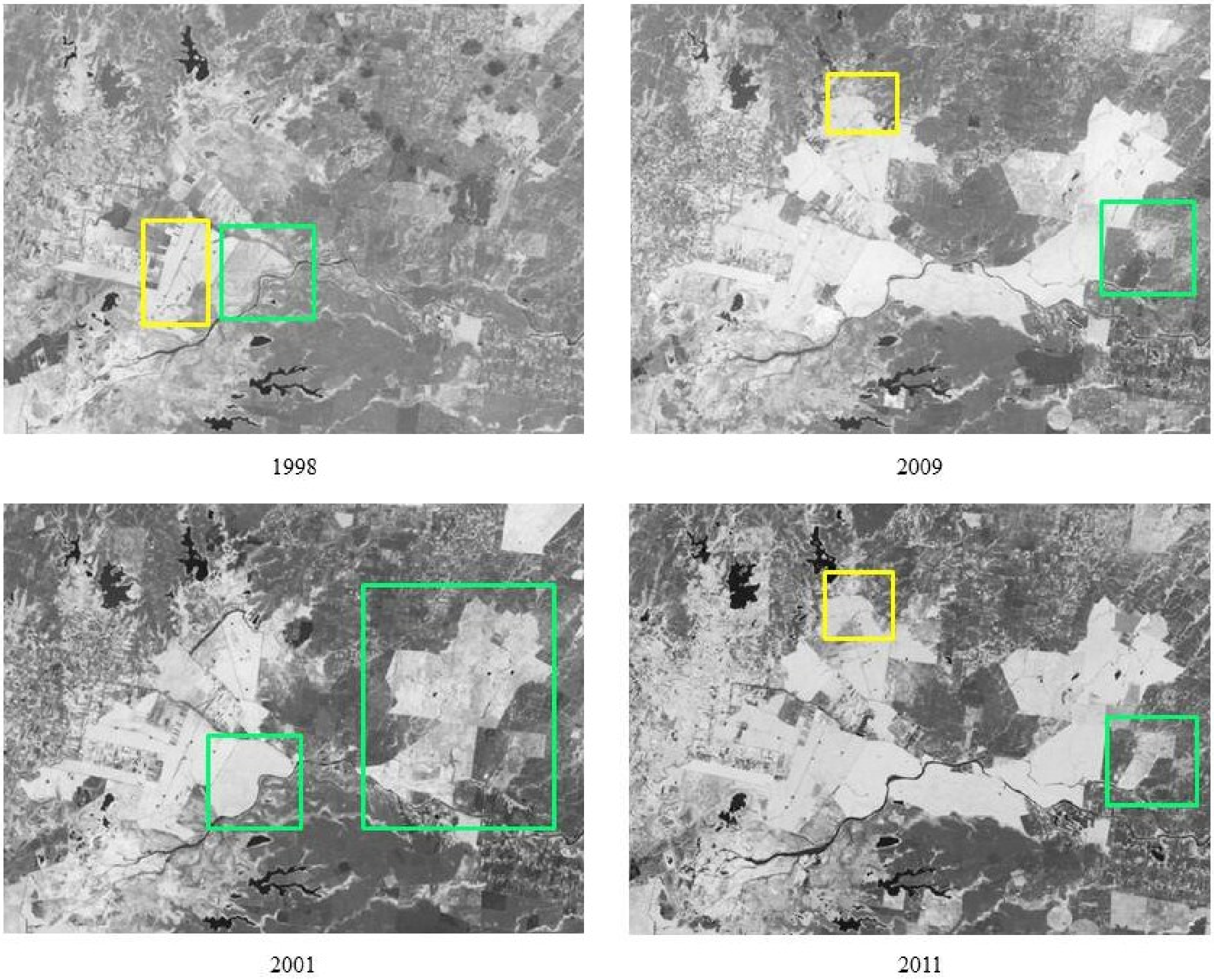


Figure 3.3. Maps of the NDVI values for the site study area for 1998, 1999, 2001, 2011. Banana plantation changes (from 660 to 940 square kilometers) indicated by yellow, palm changes (from 210 to 1,602 square kilometers) indicated by green. .

Overall changes in NDVI values as plantation areas increase are evident in the maps developed using ENVI 4.7 and ArcGIS 10 (Figure 3.3). Each pixel has a value ranging from -1 to 1 and the shading reflects these numbers; dark values are associated with numbers below zero and lighter colors area associated with higher NDVI values for each pixel. The increase in banana and plan plantation area is evident from the 1999 image compared to the 2001 image as evidenced by the lighter colors reflecting increased productivity. The change in NDVI values is even more accentuated in the 2011 NDVI map. When all pixels are combined, a picture of high to low productivity is produced.

The mean and standard deviations around the mean for NDVI for the seven different study sites (previously defined) are graphically represented in Figure 3.4, 3.5, and 3.6. The NDVI mean and standard deviation values for the dry and wet seasons are provided in the Appendix (Tables A3.1, A3.2, A3.3, and A3.4). Results of other statistical tests are discussed in a separate section.

In the NDVI means and standard deviations in Figure 3.4, 3.5, and 3.6, there appear to be differences and trends between the banana and palm plantations and each non-plantation site. As the mean NDVI increases for the banana and palm plantations, the adjacent agricultural areas are experiencing NDVI values that are below the pre-plantation values; this relation characterizes each site.

In palm plantation (Site 7), the change from non-plantation to plantation is reflected by significant increases in NDVI values and the reduction in the standard deviation. Banana plantations existed in other areas to the south, but were added after 1998. Additionally, the two plantation sites have low standard deviations, with very little variability in NDVI. NDVI contains a strong seasonal component; however, the productivity is consistent for both banana and palm during the dry season when lower productivities were recorded. Both plantation types had little seasonal and year to year variations in their NDVI values and therefore in their estimated productivity. The low variability in the plantation sites (Site 6, Site 7) reflects an increase in resource use (e.g., water and nutrients) to maintain uniform high levels of productivity.

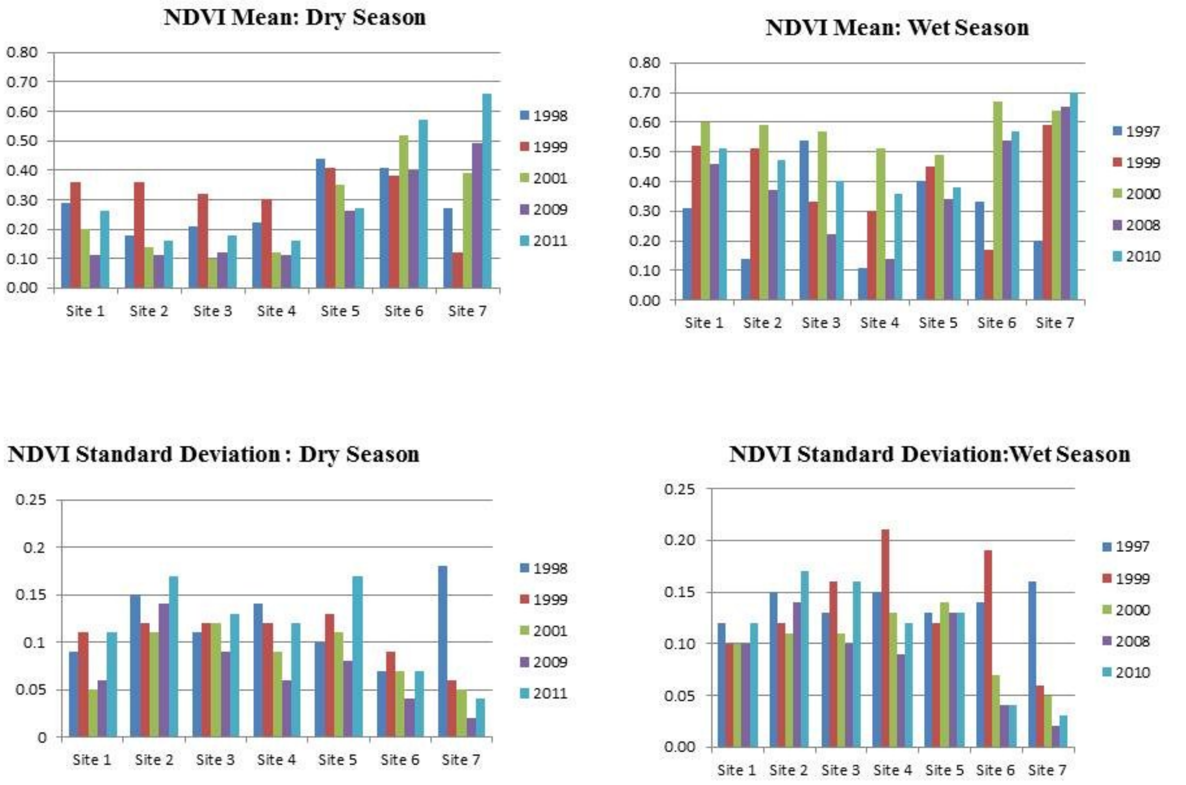


Figure 3.4, NDVI means and standard deviations, wet and dry season. Site locations are shown in Figure 3.1; site characteristics are given in Table 3.1. Generally, there are significant differences of the mean and standard deviation between the wet and the dry season, banana and palm plantation (site 6 and site 7, respectively) and each non-plantation site (sites 1-5).

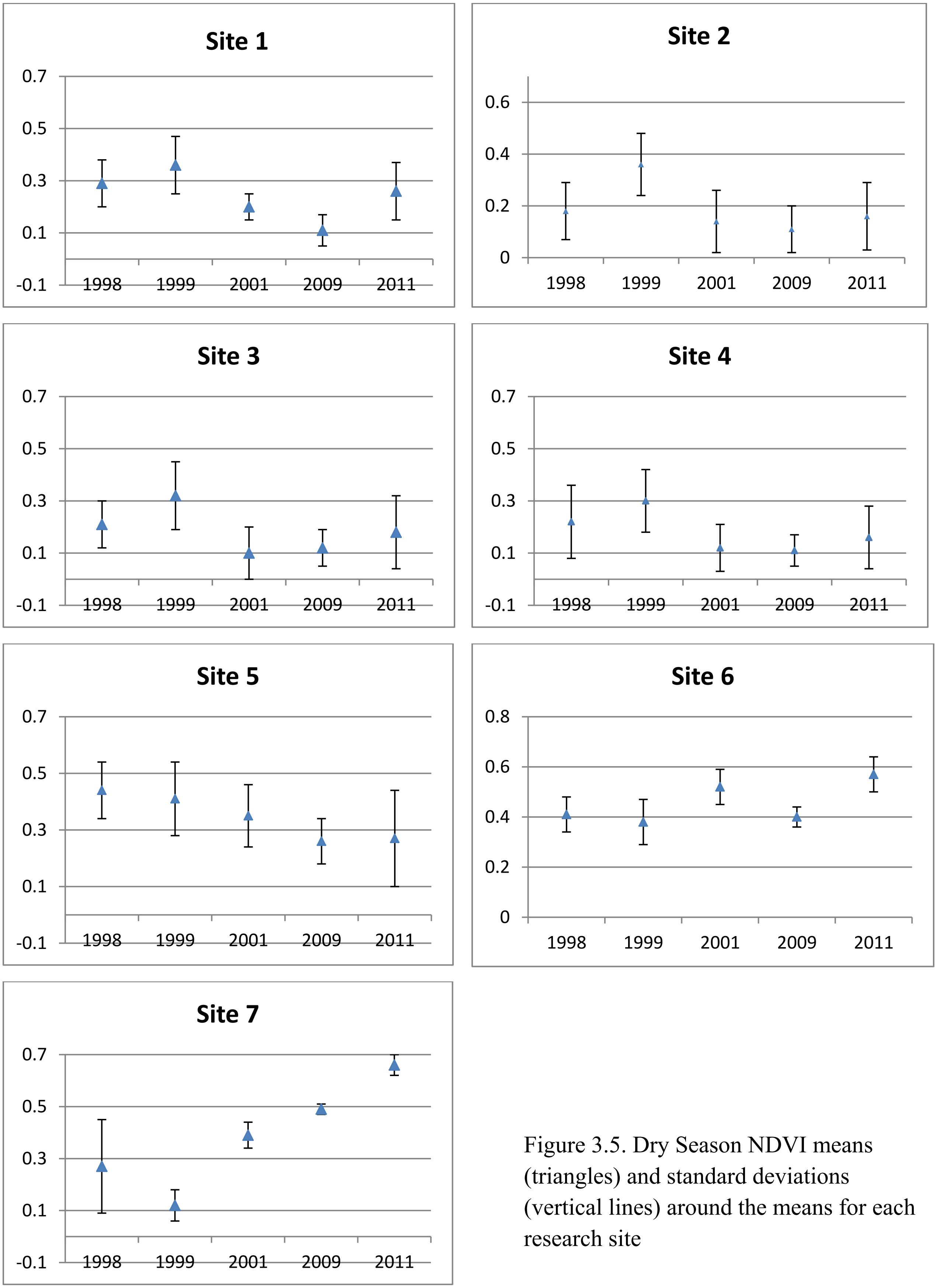


Figure 3.5. Dry Season NDVI means (triangles) and standard deviations (vertical lines) around the means for each research site

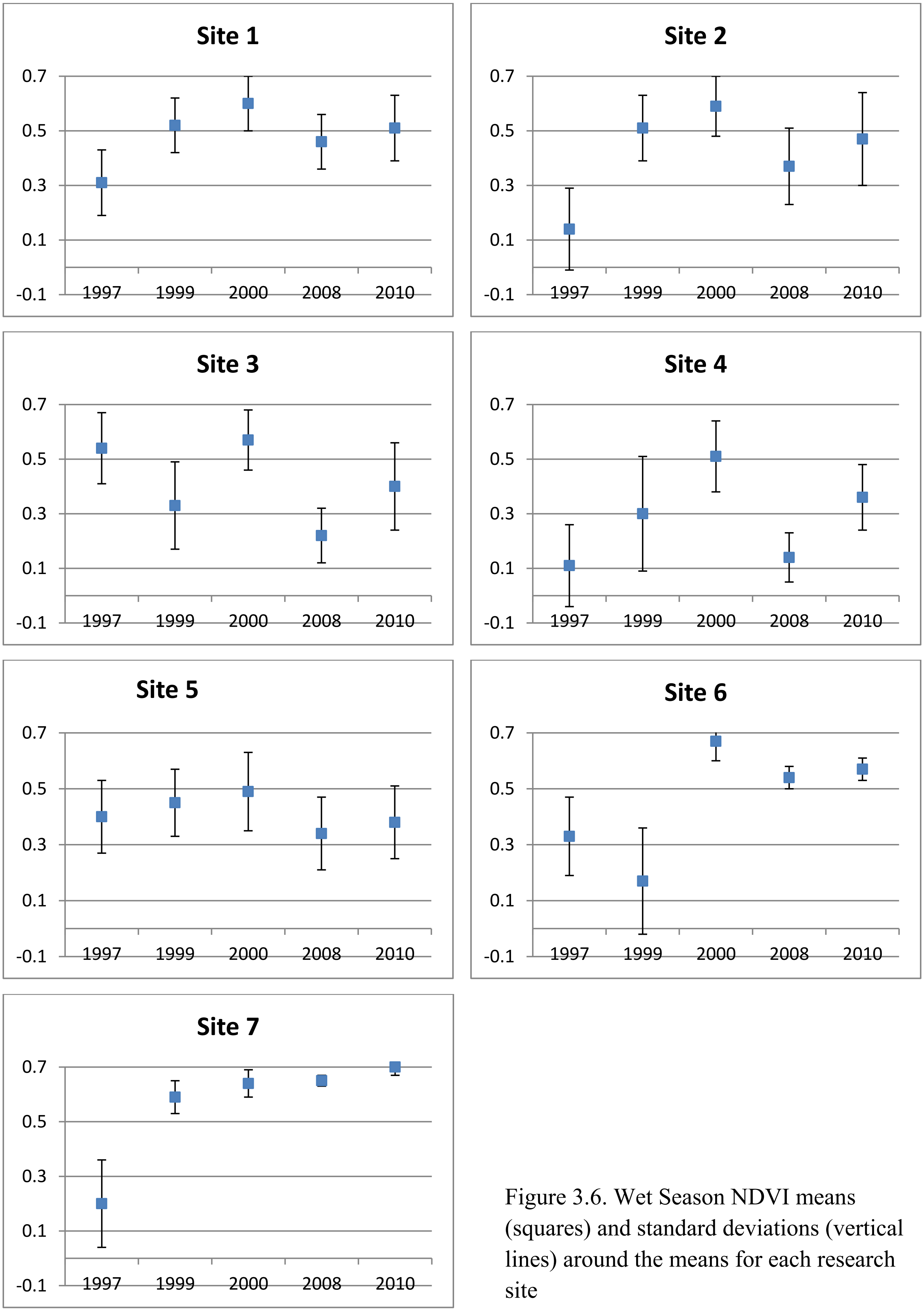


Figure 3.6. Wet Season NDVI means (squares) and standard deviations (vertical lines) around the means for each research site

Permutation Test Using Means

Statistical analysis is needed to determine the significance of the qualitative differences noted above. One such analysis is the permutation tests, which are used to determine whether an effect, such as the difference between two means, can be attributed to randomness. If the effect does not appear to be random, it is likely that there is an effect (Hesterberg et al. 2003). A value in the main body of the distribution would occur by chance, but a value in the tail of the distribution would rarely occur by chance. A permutation test is applicable to very small samples where the distribution is not readily known, making it an effective method when the data do not conform to the assumptions of a normal distribution or other commonly used statistical distributions (Ribeiro et al. 2008, Friday 1967). Instead of comparing the actual value of a test statistic to a standard statistical distribution, the reference distribution is generated from the data themselves. Additionally, results of a permutation test are valid even with observations that are not random samples of the subject population.

For this study, a non-parametric permutation test is used to determine if there is an attributable difference in mean NDVI values between sites. The null hypothesis is that an effect of the plantations is not present in the NDVI values for the selected sites in the vicinity of the plantations. The alternative hypothesis is that there is a plantation effect in the NDVI values, such that the plantations values are significantly greater than other values. For the null hypothesis to be rejected, the difference in the mean NDVI of the plantations and the mean NDVI of the vicinity sites must be in an extreme position in the distribution of differences in mean NDVI values for all possible combinations of the seven study sites (two plantation sites and five sites in the vicinity of the plantations).

The permutation distributions are created using combinations of mean NDVI values from wet season and dry season data for the seven study sites. The data for the wet season was collected in 1997, 1999, 2000, 2008 and 2010, and the data for the dry season was collected in 1998, 1999, 2001, 2009 and 2011. Given seven total sites, two of which are plantation sites (Sites 6 and 7), selecting two sites from the seven possible sites results in 21 combinations (7! / (2!*5!)). For each combination, the mean NDVI of the two selected sites is compared to the mean NDVI of five remaining sites; the value of the statistic observed is the difference between these mean NDVIs. The resulting frequency distribution for wet season is shown in Figure 3.7 and Table A3.5. The resulting frequency distribution for dry season is shown in Figure 3.8 and Table A3.6.

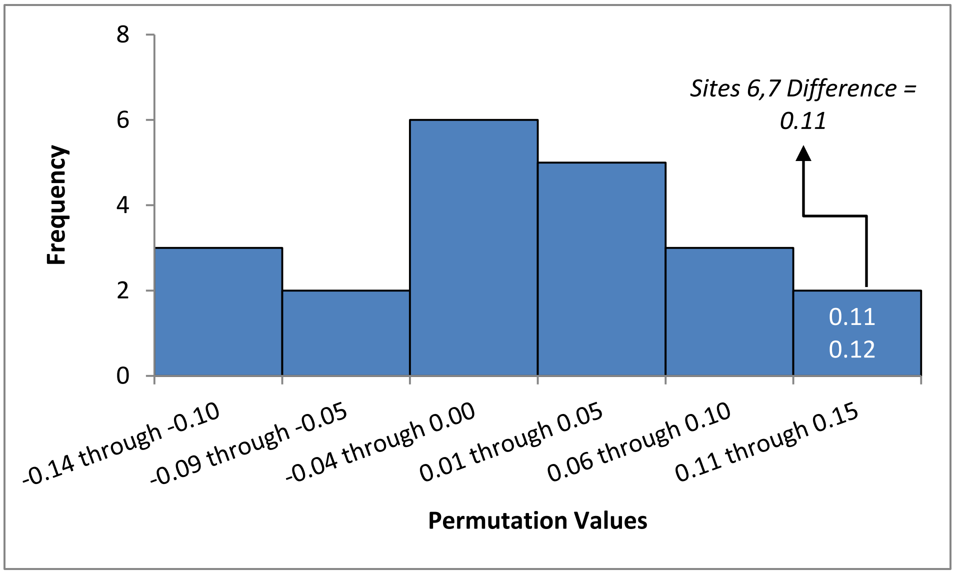


Figure 3.7. Histogram of Wet Season permutation values 1997-2010.

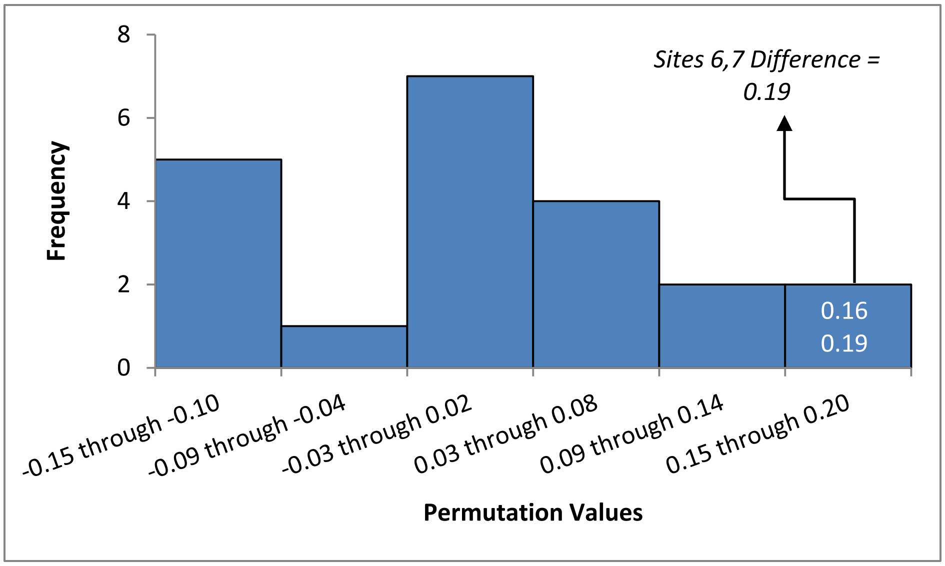


Figure 3.8. Histogram of Dry Season permutation values 1998-2011.

For the wet season over all time periods, the difference between the mean NDVI of the two plantations sites (Sites 6 and 7) and the mean NDVI of the five vicinity sites is 0.11. One of the other twenty difference permutations is greater than or equal to 0.11 (Figure 3.7, Table A3.5); therefore, the p-value for the wet season is 2/21, or 0.095. For the dry season over all time periods, the difference between the mean NDVI of the two plantations sites and the mean NDVI of the five vicinity sites is .019. None of the other twenty difference permutations is greater than or equal to 0.19 (Figure 3.8, Table A3.6); therefore, the p-value for the dry season is 0.048. Testing with a level of confidence α = 0.10, both tests result in the rejection of the null hypothesis and the finding that there is a plantation effect in the NDVI values for both the wet and dry seasons.

Exploring the data further, for 1997 wet season (the earliest wet season data), the difference between the mean NDVI of the two plantations sites and the mean NDVI of the five vicinity sites is -0.04. Eleven of the other twenty difference permutations is greater than or equal to this value (Figure 3.9; Table A3.7); therefore, the p-value for this wet season data is 0.57 for this data set. The wet season data for 2010 results in a difference of 0.21 between the mean NDVI of the two plantations sites and the mean NDVI of the five vicinity sites. None of the other twenty difference permutations is greater than or equal to this value (Figure 3.10; Table A3.8); therefore, the p-value for this wet season data is 0.048.

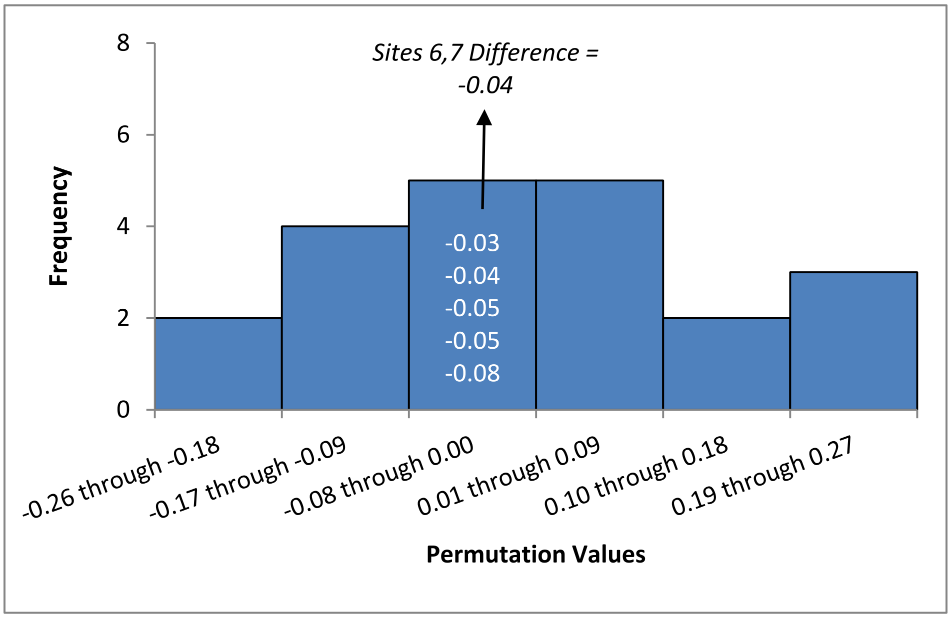


Figure 3.9. Histogram of Wet Season permutation values 1997.

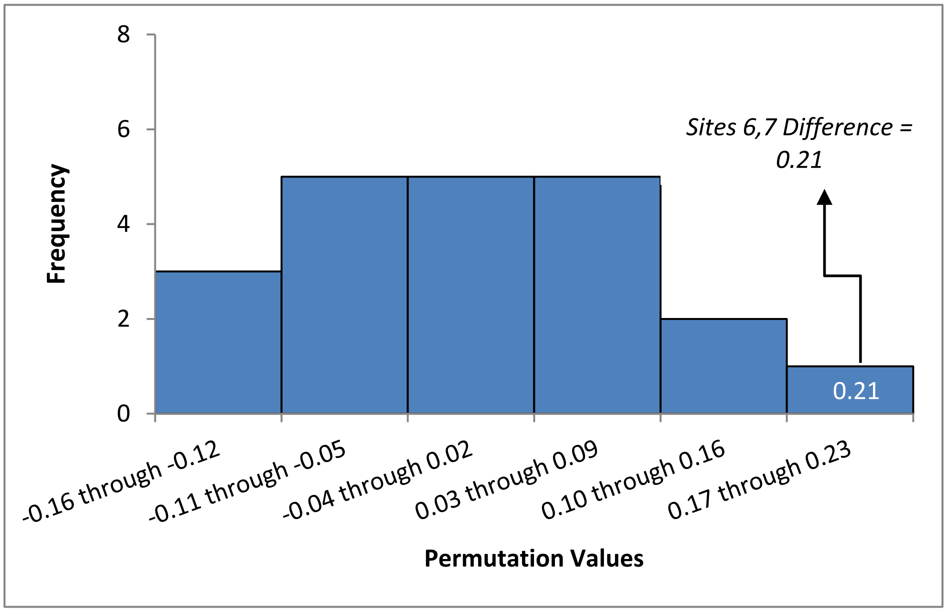


Figure 3.10. Histogram of Wet Season permutation values 2010.

The difference between the mean NDVI of the two plantations sites and the mean NDVI of the five vicinity sites for the 1998 dry season observations (the earliest dry season data) is 0.07 (Figure 3.11; Table A3.9). Four of the other twenty-one difference permutations are greater than or equal to 0.11; therefore, the p-value for this dry season data is 0.24. Comparatively, the 2011 dry season data results in a difference of 0.41 (Figure 3.12; Table A3.10); none of the other twenty-one difference permutations is greater than or equal to that value, resulting in a p-value of 0.048.

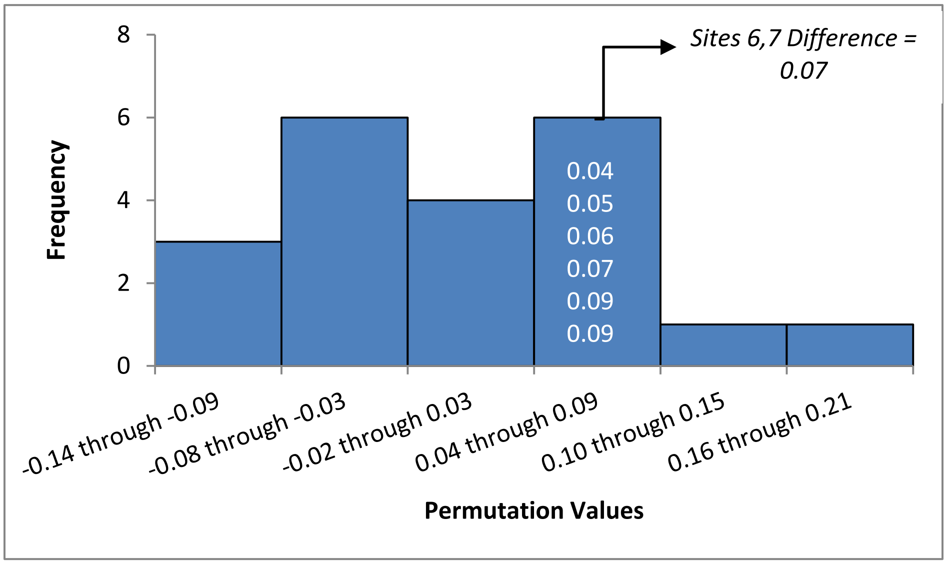


Figure 3.11. Histogram of Dry Season permutation values 1998.

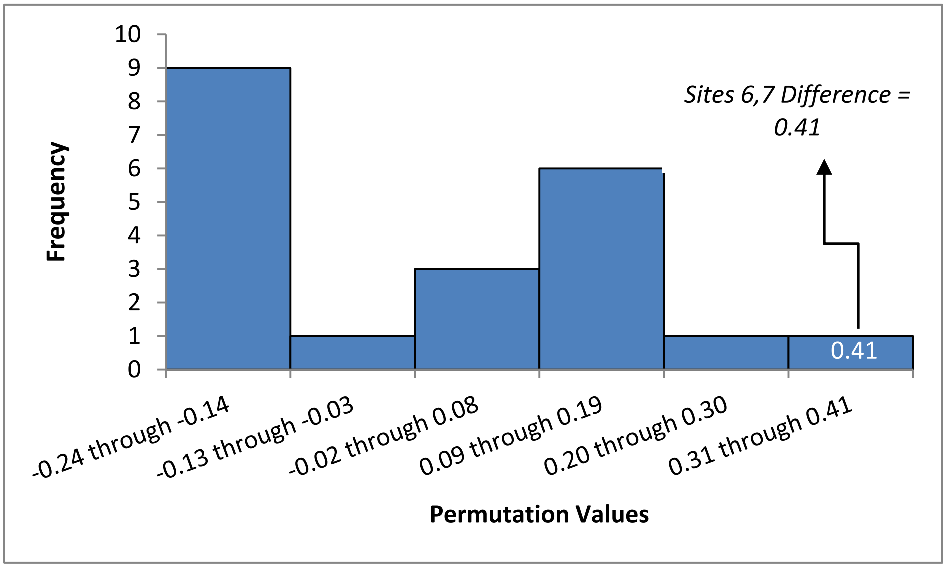


Figure 3.12. Histogram of Dry Season permutation values 2011.

In order to assess the temporal relationship for the p-values, a Spearman's rank correlation coefficient was calculated using the year of the measurement and the resulting p-value for the permutation test for each corresponding year and for each season, wet and dry (Table 3.2). This non-parametric method was used as a measure of statistical dependence between two variables. Resulting values are from +1 to -1 where a Spearman's rho (r_s) of +1 indicates a perfect association of ranks, a r_s of zero indicates no association between ranks and a of -1 indicates a perfect negative association of ranks. The closer r_s is to zero, the weaker the association between the ranks (Zar 1999). Spearman's rank correlation coefficients were calculated between plantation NDVI p-values and time periods using IBM SPSS v.19.

Table 3.2. Plantation P-values by Year and Season

Wet Season			**Dry Season**	
Year	Plantation *p-value*		Year	Plantation *p-value*
1997	0.57		1998	0.24
1999	0.67		1999	0.86
2000	0.24		2001	0.05
2008	0.05		2009	0.05
2010	0.05		2011	0.05

The results of this test indicate for both wet and dry season a r_s value of -0.872, with a level of significance of 0.027. These results are further evidence of a measureable change over time of between the plantations and the surrounding sites.

Variability Trend Analysis

In order to determine what type of trend is occurring within the different sites regarding the variability over the time period of analysis, a non-parametric slope estimator developed by

Theil Theil and Sen (Conquest 2000) is computed to estimate the trend. The trend slope is expressed by change per unit time, and the slope is calculated for each pair of data points for each time period. If all values are distinct and there are no missing data, there will be a number of computed slopes. Once the median slope is determined, the intercept may be defined.

The results of this estimation for the wet season is illustrated in Figure 3.13 and given in Table A3.11. The trend has been declining for both the banana plantation (Site 7) and palm plantation (Site 6). Site 1, the site most removed from the vicinity of the plantations, has had no real changes in variability as compared with an increase in Site 2 and small increases in Sites 3 and 5. The trend for Site 4 is similar to the plantations, but with a different magnitude. The breaks in slopes at year 2000 for all sites, except Site 1, may be indicative of the introduction or expansion of plantations.

The results of the estimation for the dry season are illustrated in Figure 3.14 and given in Table A3.12. The palm plantation (Site 7) variability decreases more than banana plantation (Site 6) variability. Variability slope of Site 1 is flat to slightly increasing as compared with the flat trend line observed in the wet season data. Site 2 exhibits a similar pattern to its wet season data. Sites 3 and 5 show upward trends, as compared to slight downward trends during the wet season. Site 4 continues to exhibit a similar decreasing variability, as observed with the banana plantation. The breaks in slopes for all sites for year 2000, except Site 1, reflect the change in variability due to the introduction or expansion of plantations.

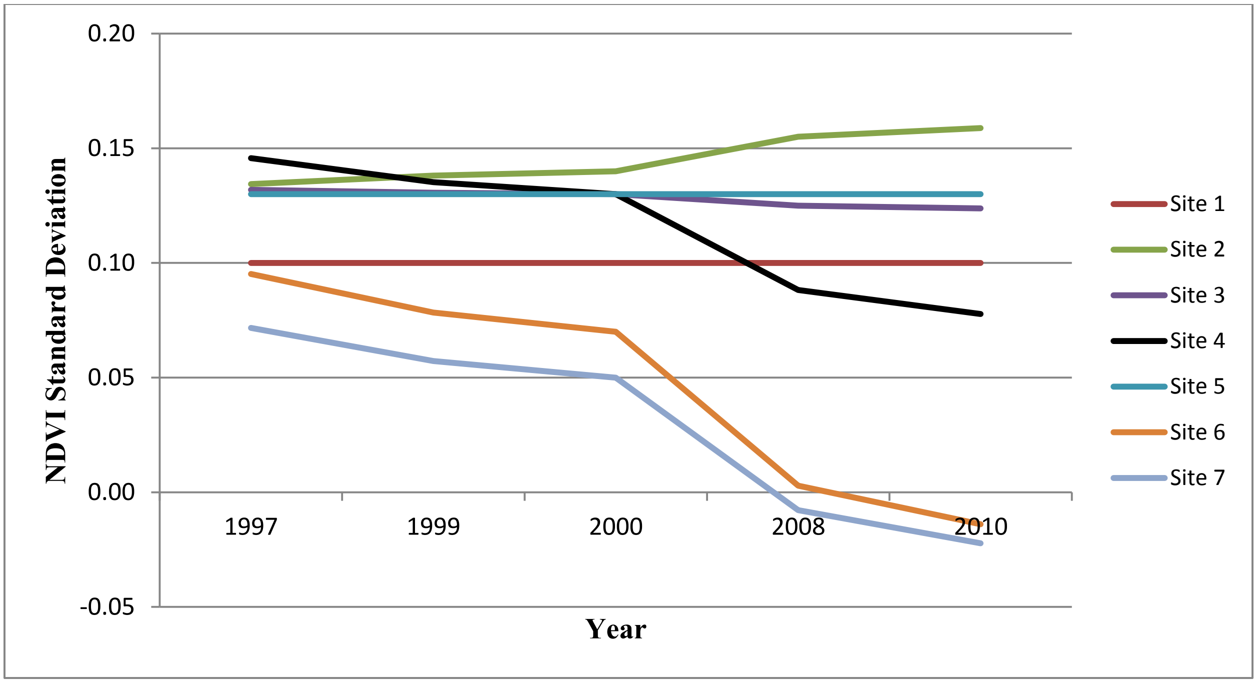


Figure 3.13. Wet Season NDVI trend values standard deviation. The breaks in slope reflect the changes due to the introduction or expansion of plantations.

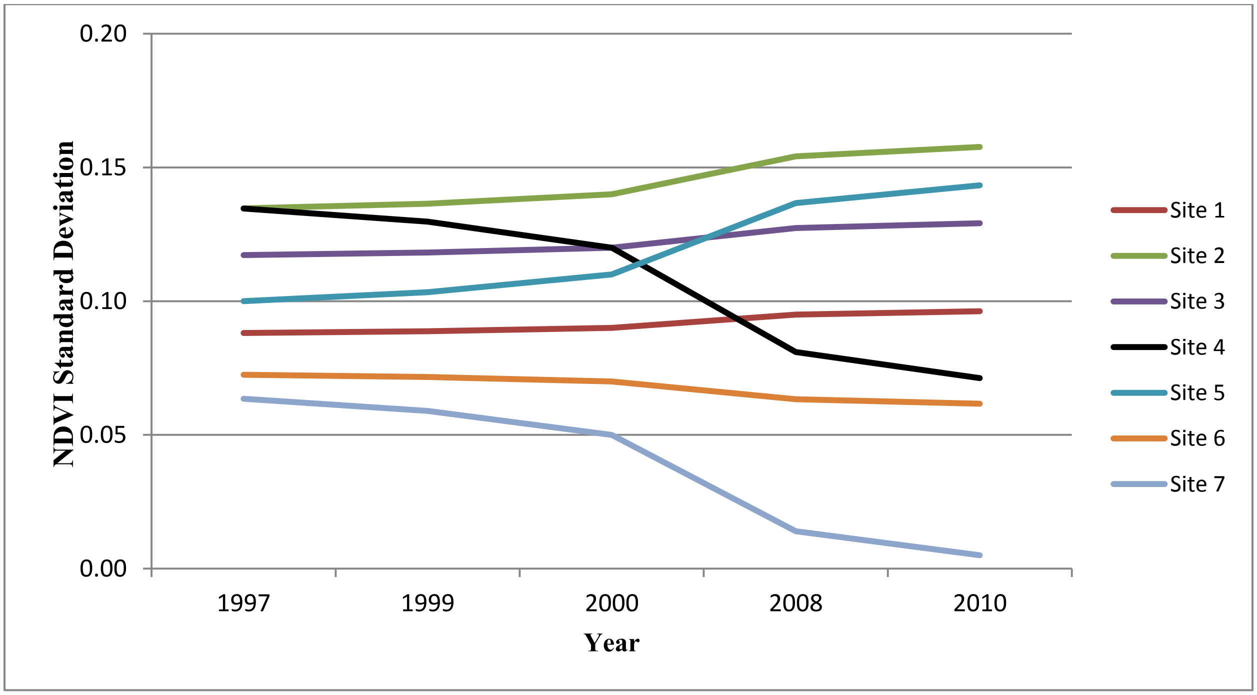


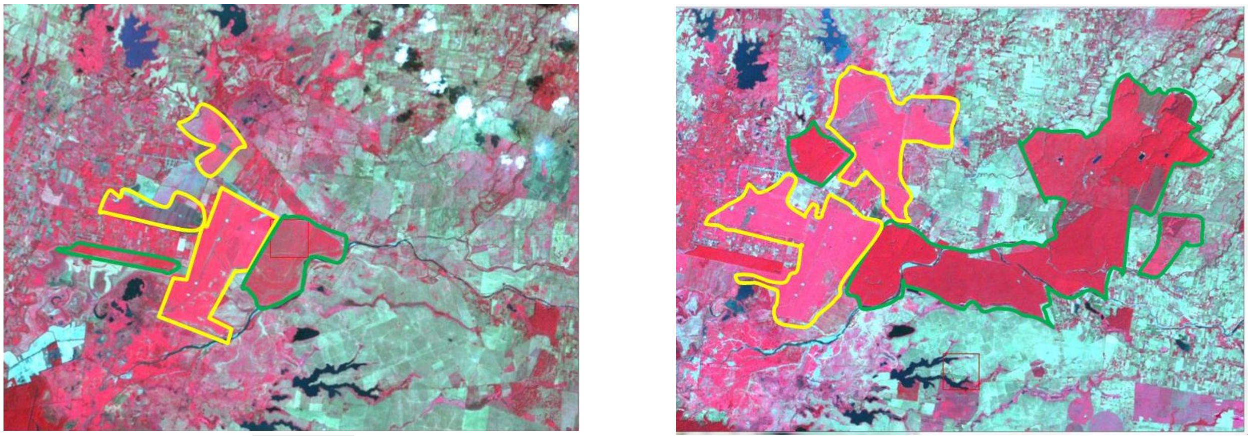
Figure 3.14. Dry Season NDVI trend values standard deviation. The abrupt slope changes reflect the changes introduced by the plantations.

Conclusions

Land-use change in the Pacific coastal plain of Guatemala from natural land to banana and palm plantations has occurred increasingly over the last 20 years. This research, designed to evaluate the effects of these land-use changes by remote-sensing analysis, has proved that the changes may be estimated with a reasonable level of accuracy by the methods employed in this study. Stated differently, the previously stated hypothesis; i.e., that lands adjacent to plantations have been adversely affected by the introduction and expansion of banana and palm plantations as measured by remotely sensed derived vegetation indices, has been validated. This is an important finding, given the need to estimate the effects of land-use change in many other tropical settings.

Estimates of the increase in area of banana plantations, derived from Landsat satellite imagery, are approximately 660 square kilometers to 940 square kilometers for the time period (dry season) from 1998 to 2011. The area of palm plantations has increased from 210 square kilometers to 1,602 square kilometers. Figure 3.15 illustrates these changes from 1998 to 2011. These land-use and land-cover changes appear to have resulted in significant changes in the land productivity of lands adjacent to plantations. It is suspected that the pressure of these changes has pushed the land-use well toward unsustainability.

The analysis reveals productivity patterns and illustrates the use of satellite imagery to measure land-cover and land-use change over time in order to begin to interpret the relationship between landscape change and resulting impacts. Limitations exist in the study because of the frequency and quality of Landsat data to properly measure the temporal dynamics in play in conjunction with land-use changes. However, the Landsat imagery clearly shows the increase in plantations since 2000.



1998

2011

Figure 3.15. Plantation Areas: Banana is outlined in Yellow; Palm in Green. Areas of high productivity are Pink; low productivity is Green or Gray. Areas derived from Landsat images and imposed onto a 4,3,2 red band combination to accentuate the level of vegetation productivity.

Analysis of the remote-sensing data at the study sites shows the increase of NDVI over time for the plantations and a varied, but somewhat downward trend for the non-plantation sites. A significant result is that the consistent high level of productivity for the banana and palm plantations is in sharp contrast to the productivity of non-plantation sites.

This data can serve as a starting point to determine what areas may be the most suitable for restoration given historical land-use changes and what areas may provide the best chance of restoration requiring the least amount of effort. Given the results of the statistical analysis and assuming the effect of the plantations is to reduce variability, if the standard deviation of a site is negatively correlated to the mean, the NDVI may be increasing because of the presence of plantations. For example, dry-season data may indicate that Site 2 would be a good candidate for restoration given the significant decline in the NDVI, and also given the apparent negatively correlated relationship between NDVI mean and standard deviation. Because this is a characteristic of the plantations, as the variability declines, restoration would result in increased productivity increases, thereby providing improvement in the long-term.

Using the Site 1 as a reference site, the increases in Site 2, particularly during the dry season are more significant than in other areas. However, it may be more appropriate to restore a site where the change is not as significant and correlates with variability (e.g., Site 4). As previously mentioned, this is a starting point, with other local data and input needed to identify the causal factors of land-use change for this landscape. Spider diagrams, hypothetically introduced in the beginning of this chapter, can illustrate the trade-off between different actions. These trade-offs are evident in the NDVI mean values from 1999-2011 as resources are shifted to plantations. The change between two different time periods, illustrated in Figure 3.16, can be used as a filter to begin the process of analyzing the impact of land-use change.

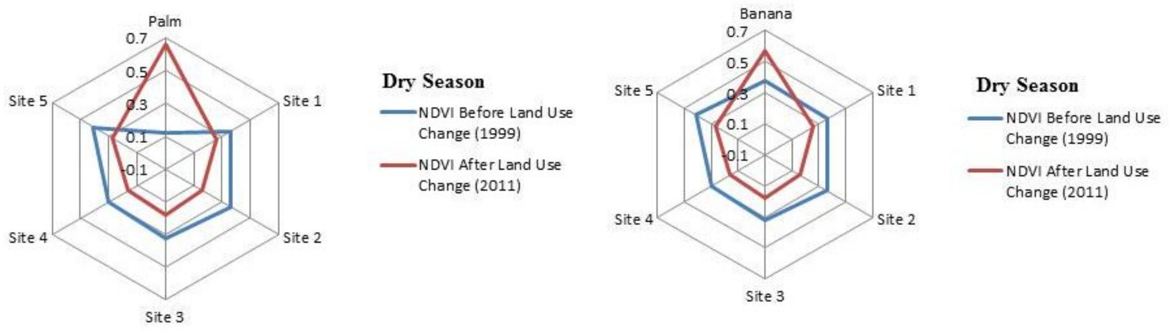


Figure 3.16. NDVI change between two different time periods.

Chapter 4: Water Quality Analysis

Land-use and Land-cover Change

Land conversion and agricultural intensification alter the ecological interactions and patterns of resource availability in ecosystems with local, regional, and global environmental consequences. Intensification of agriculture by use of high-yielding crop varieties, fertilization, irrigation, and pesticides has contributed substantially to the tremendous increases in agricultural production over the past 50 years (Uriate et al. 2011; Matson et al.1997). Agricultural practices can affect soils to the extent that the result is soil malfunction and, eventually, the degradation of soil and water resources. Effects of land-use can be observed in streams, which are vulnerable to potential damage because of the link to anthropogenic changes (Maloney et al. 2011; US EPA 2006, WWF 2006). Nutrient inputs as a result of intensification exceed natural sources and have widespread effects on water quality and coastland freshwater ecosystems. (Foley et al.2005; Bennett et al.2001; Matson et al.1997; DeFries et al.2004).

Intensive agriculture increases erosion and sediment load and leaches nutrients and agricultural chemicals to groundwater, streams, and rivers. Agriculture has become the largest source of excess nitrogen and phosphorus to rivers and coastal ecosystems (Bennett et al. 2001, Carpenter et al. 1998b). In many of the world's agricultural lands, nutrient transport by fertilization has overwhelmed natural nutrient cycles. The excessive application of fertilizers (including quantity and frequency of application) usually exceeds the functional ability of the soil to retain and transform the nutrients and synchronize the availability of nutrients with crop needs. In many cases, the saturation of the soil with nitrogen or *phosphate has* led to leaching of nitrates into shallow groundwater and saturation of the soil with phosphate, which may also move into groundwater (Breeuwsma and Silva, 1992). In intensive horticultural systems, interaction between high fertilizer inputs and major irrigation schemes enhances nitrate leaching and non-point-source pollution of surface and ground water.

Effects

In aquatic ecosystems, excess nutrients cause diverse problems such as toxic algal blooms, loss of oxygen, fish kills, loss of biodiversity (including species important for commerce and recreation), loss of aquatic plant beds and coral reefs, and other problems. Nutrient enrichment seriously degrades aquatic ecosystems and impairs the use of water for drinking, industry, agriculture, recreation, and other purposes (Maloney et al.2011, Zalidas et al. 2002). In Latin America and Africa, there is a positive correlation between malarial mosquito larvae, algal productivity and levels of inorganic nitrogen *(N)* in surface waters (Rejmankova et al.1991, Townsend et al.2003).

Although stream water chemistry recovers relatively faster than catchment changes, such as woody debris removal, water-quality effects may still exist for decades; the indiscriminate application of pesticides can also directly kill non-targeted species. Water quality of streams affects habitat, as stream biota are strongly controlled by available habitat. This biota may or may not be able to rebound after their habitat recovers. Both past and contemporary land-uses can affect stream communities (Burcher et al. 2007; Maloney et al. 2011). Streams have a high potential for reflecting past land-use effects because stream impairment has been strongly linked to anthropogenic stressors. For example, biocide residues in waters, sometimes directly through spray drift and persistent pesticides released decades ago, are still detectable in Antarctica and therefore presumably throughout the planet (Moss 2008).

Effects of land-use change can be a cascade effect, with the change resulting in responses from hydrologic, erosional and depositional elements effecting biota and water quality (Burcher et al.2007). Indiscriminate application of pesticides and fertilizers can pollute surface and groundwater sources. Rainfall causes pesticide residues to penetrate the soil, making them available to subterranean organisms, and runoff carries residues from the site of application into aquatic systems. Fungicide application is suspected to be responsible for the copper contamination of some Costa Rican soils, and these soils may be unsuitable for most agricultural production. Humans and wildlife can be exposed to pesticides through aerial applications, food items, and contaminated drinking water (Henriques 1997).

Measurements

Non-point inputs of nutrients are difficult to measure and regulate because the activities that produce these compounds are distributed over wide areas of land. These effects can also be variable in time due to effects of weather and climate. A sustainable development model requires analysis of water quality and environmental issues, together with the related economic and human systems involved. For example, it is not possible to take an individual agricultural activity, the spraying of a particular pesticide at a known dose rate, the application of a specific amount of ammonium nitrate fertilizer, and measure precisely the effects of these on the reproduction of a particular fish species, or the extent of silting of a river stretch. The effects can be measured in a general way; then assumptions and cause and effect correlations can be made. (Haygarth and Jarvis 2002). Impacts of agriculture are often paralleled by human activities and natural occurrences. For example, compounds from the mineralization of organic nitrogen in agricultural and undeveloped soils, from wastewater treatment works, from oxidation of nitrogen oxides in the atmosphere, as well as from fertilizer runoff, may be simultaneously present (Moss 2008; Haygarth and Jarvis 2002).

Water Pollution and Agrochemicals

Palm Plantations

Palm oil processing uses large quantities of water in processing mills where oil is extracted from the palm fruits. It is estimated that for 1 ton of crude palm oil produced, 5 - 7.5 tons of water ends up as Palm Oil Effluent (POME) (Okwute and Isu 2007, Ahmad et al. 2003). This POME has a high content of degradable organic matter along with palm oil (Ahmad et al. 2003) For every metric ton of palm oil produced, 2.5 metric tons of effluent are generated from processing the palm oil in mills. During the extraction of crude palm oil from the fresh fruits, about 50% of the water results in palm oil mill effluent (POME). The raw or partially treated POME has an extremely high content of degradable organic matter, which is due in part to the presence of unprocessed palm oil (Ahmad et al. 2003; Okwute and Isu 2007). If left untreated and disposed of in streams, this wastewater can cause oxygen depletion and other reductions in the biological functioning of waterways. (Ahmad et al. 2003). It has been observed that most of the POME produced by the small-scale traditional operators undergoes little or no treatment and is frequently discharged into the surrounding environment unless there are regulations preventing such treatment of waste.

Although palm oil production requires less fertilizer per unit of output than other oilseed crops, nutrients such as nitrogen, phosphorus, and potassium are applied regularly to oil palm trees: CH_4N_2O (urea), KCl, $MgSO_4$ (2 times/year); triple super phosphate and $CaCO_3$ (one time/year) (Tuinstra 2009). The main pesticide used on plantations is poison to control rats. Pesticides can be used to control the *Oryctes rhinoceros* beetle, and bagworms can require treatment. Some herbicides are used, particularly when plantations are being established for stem rot. Once the trees grow and produce a canopy that shades the ground, the use of herbicides is greatly reduced.

Banana Plantations

Banana plants require frequent and intense applications of fertilizer and pesticides. Banana plants are attacked by over 200 insect pests that either directly damage plants or act as pathogen vectors. Banana plants are highly susceptible to fungal infestations. Soils must have good drainage capacities and excess water must be removed. Fungal diseases are one of the main problems on banana plantations (Henriques et al. 1997). Fungicides are applied to the plantations primarily by aerial spraying in 1 to 2 week cycles. The spraying compounds consist primarily of petroleum oil, or oil, mixed with fungicides. This is a rapid technique for delivering pesticides to large areas, but runoff from pesticide storage sites and drift of the chemical from target sites can inadvertently contaminate neighboring homes, streams, and wetlands. Herbicides are also applied to fungus-infected plants to destroy the plant and reduce spread of the disease. Plastic bags are coated with chlorpyrifos, a neurotoxic pesticide, and wrapped around the maturing fruit to protect it from insect damage during the final growth stages. The proper disposal of these bags has been a problem for many growers. Organophosphates and carbamates are most commonly used pesticides.

Fertilization is necessary for the proper soil nutrients to grow bananas. Nitrogen, potassium, phosphorous, and calcium are essential nutrients required for banana plantation soils (Smith et al. 1992). All banana plants have high nitrogen and potassium requirements, and all plantations apply these two elements at the general rates of 300 to 600 kg N/ha four or more times a year and 400 to 800 kg K/ha once or twice a year (Henriques et al. 1997). Fertilizer is applied to plant through irrigation, by granular application, or by aerial application. Bananas also require regular applications of calcium, magnesium, sulfur, and zinc to maintain the extent of soil productivity necessary for fruit production.

Water Quality Study

In rural San Marcos, Guatemala, banana and palm oil plantations since 2000 have introduced significant alterations to the environment, including the diversion of a river from its previous course, the partial elevation of its banks, and the destruction of multiple wetlands areas. In recent years, surrounding peasant communities have experienced massive flooding. The resultant destruction of up to 90% of annual harvests, exacerbated by the declining availability of fish (once a vital protein source), have raised food security concerns. In the wake of these changes, residents also complain about increasing skin and gastrointestinal ailments, problems they attribute to poor water quality.

In 2010, the University of Washington Center for Human Rights established a partnership with the Pastoral de la Tierra San Marcos, a peasant rights advocacy organization representing the interests of the affected peasants. Since then, a team of UW scholars including faculty, graduate, and undergraduate students in Forest Resources, Engineering, Law, International Studies, and Geography, have participated in research focusing on different dimensions of the problem. The water quality study was developed in the region where sampling was from stream (where residents fish, bathe, and wash clothes) but also from drinking water wells, given input from the Pastoral de la Tierra. The team conducted water quality testing in February 2011, June 2011, December 2011, and July 2012 to quantify the impact of fertilizers, herbicides, fungicides, and pesticide use on the local waterways and drinking-water wells.

Sampling Locations

Over the course of the three research trips, a total of 56 samples were taken from 28 different locations (Figure 4.1) during the periods of February 2011, June 2022, December 2011, and July 2012, which represent two dry seasons and two wet seasons. Sampling locations were determined by the proximity to plantations and access to the river, as well as input from the local advocacy organization. Many locations were difficult to access consistently during the sampling periods. Also, community and the informational needs of the local partner varied somewhat between the sampling trips.

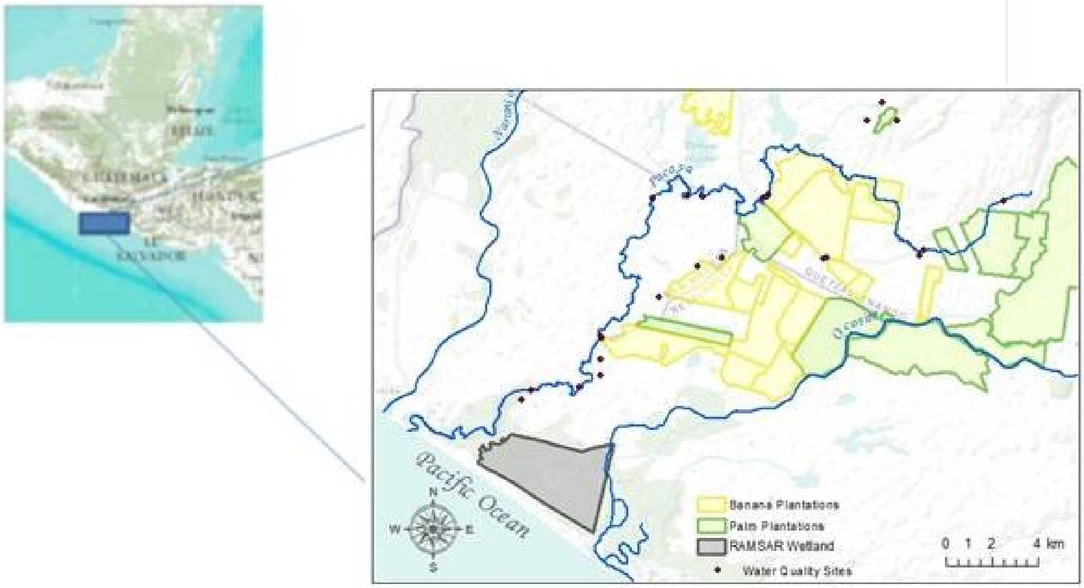


Figure 4.1 Locations of sampling sites.

Water Quality Testing Procedure

Water quality samples were tested using a portable colorimeter to test ammonia, chloride, conductivity, dissolved oxygen, hardness, nitrate, nitrite, oxygen-reduction potential (ORP), pH, phosphate, resistivity, salinity, specific conductance, suspended solids, total dissolved solids, temperature, and turbidity. In order to test for arsenic, cadmium, chromium, copper, lead, and selenium 15-mL samples were stabilized in the field with nitric acid for analysis in the University of Washington Civil and Environmental Engineering's laboratory, using an ICP-MS. The variables with significant values are listed in Table 4.1. The values of these chemicals measured were compared to applicable water quality standards. Guatemala's Ministry of Environment and Natural Resources (MARN) has not yet established specific water quality standards for the country. The World Health Organization (WHO) standards were used for drinking water standards in addition to the applicable United States Environmental Protection Agency (EPA) and Washington State standards. Not all variables tested have specific standards; however, the standards available are noted in Table 4.2.

Table 4.1. Significant Constituents/Parameters, Their Symbols and Units

Constituent/Parameter	**Symbol**	**Units**
Arsenic	As	ppb (µg/L)
Chloride	Cl	mg/L
Copper	Cu	ppb (µg/L)
Conductivity		µS /cm
Dissolved Oxygen	DO	mg/L
Nitrate	NO_3	mg/L
Nitrite	NO_2	mg/L
pH	pH	pH units
Phosphates (Phosphorus)	P	mg/L
Salinity	Na	ppt
Total Dissolved Solids	TDS	mg/L
Suspended Solids	SS	mg/L
Turbidity	Turb	NTU

Table 4.2. Water Quality Standards for Drinking Water

Constituent/Parameter	**World Health Organization Standard**
pH	6.5-8.5
Copper	2 mg/L
Nitrates (mg/L)	50 mg/L total nitrogen
Nitrites (mg/L)	0.2 mg/L long-term, *3* mg/L short-term
Chloride (mg/L)	250 mg/L
Arsenic (ppb)	10 PPB / 10 µg/L
Salinity, sodium (ppt)	0.2 ppt / 200 mg/L
Total Dissolved Solids	1,000 mg/L
Turbidity	5 NTU
Constituent/Parameter	**Washington State / U.S. Environmental Protection Agency**
Dissolved Oxygen	6.5 mg/L
Total Dissolved Solids (g/L)	500 mg/L
Phosphates	.096 hypereutrophic

Water Quality Results

Heavy Metals

These elements have high densities, and as accessories, they are also referred to as trace elements. They are commonly present in agro-ecosystems, where they present environmental issues. These groups of elements include copper, cadmium, lead, selenium, zinc, mercury, chromium, and molybdenum. Some are micronutrients and are required by some organisms, but, some can reach levels in soils that are toxic to plants, leading to toxicity in animals and plants and reduced crop production (deVries et al.2002).

In the study area tests were made for the presence and abundance of arsenic, copper, selenium, lead, chromium, and cadmium. Arsenic and copper are the elements that had significant levels.

Arsenic

Arsenic is usually found in groundwater at concentrations of less than 1-2 μg/L or 1-2 ppb. Palm plantations use arsenic for rodent control. According to Washington State's surface water standards, a 360 μg/L one hour concentration cannot be exceeded more than once every three years on the average and a 190 μg/L 4-day average concentration cannot be exceeded more than once every three years on the average. According to WHO standards, drinking water should be less than 10 μg/L or 10 ppb. Above normal groundwater levels but can also be attributed to naturally occurring high levels in the surrounding soils. Most exposure from arsenic is through food and drinking water. High exposure to arsenic can result in dermal lesions such as hyper- and hypopigmentation, peripheral neuropathy, skin cancer, bladder and lung cancers, and peripheral vascular disease (Kitchen and Conolly 2010).

As observed in Figures 4.2 and 4.3, wet season values were less than dry season values as might be expected. The two high values that exceed WHO standards were located near the wetland and near banana and palm plantation in the northeast portion of the study area.

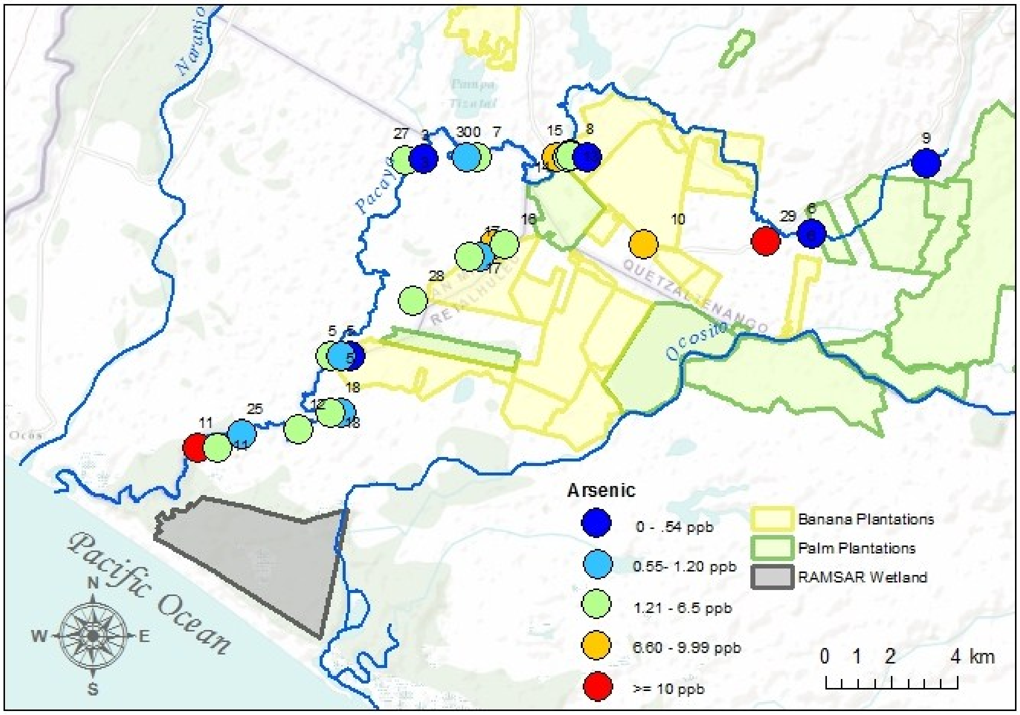


Figure 4.2. Dry Season locations and arsenic values.

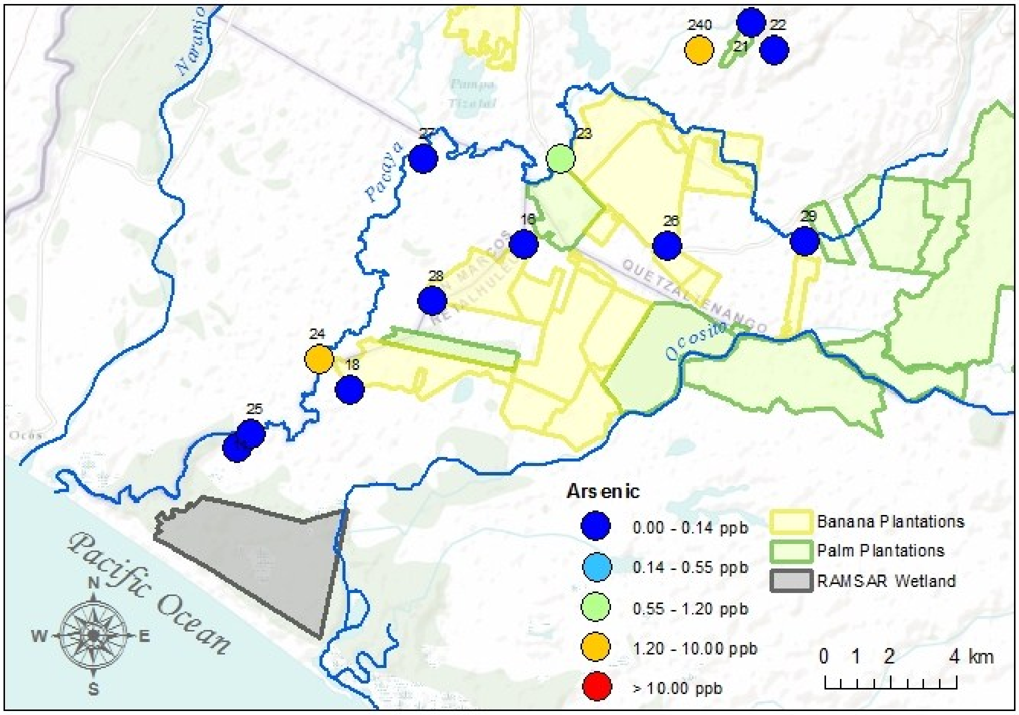


Figure 4.3. Wet Season locations and arsenic values.

Copper

The WHO standard for copper is 2 mg/L/(2000 PPB).. Copper is a naturally occurring element and can be present in surface waters at concentrations that range from 0.2 µg (microgram)/L to 30 µg/L (Bowen 1985). Copper may also enter the environment through natural processes, such as volcanic eruptions and as a result of agricultural activities (e.g., through its use as a mildewcide, fungicide, and/or algaecide). High values were recorded in the Reserva Natural Privada Manchon Guamucha wetland. In addition, values just over the WHO standard were measured adjacent to banana and palm plantations (Figures 4.4. and 4.5).

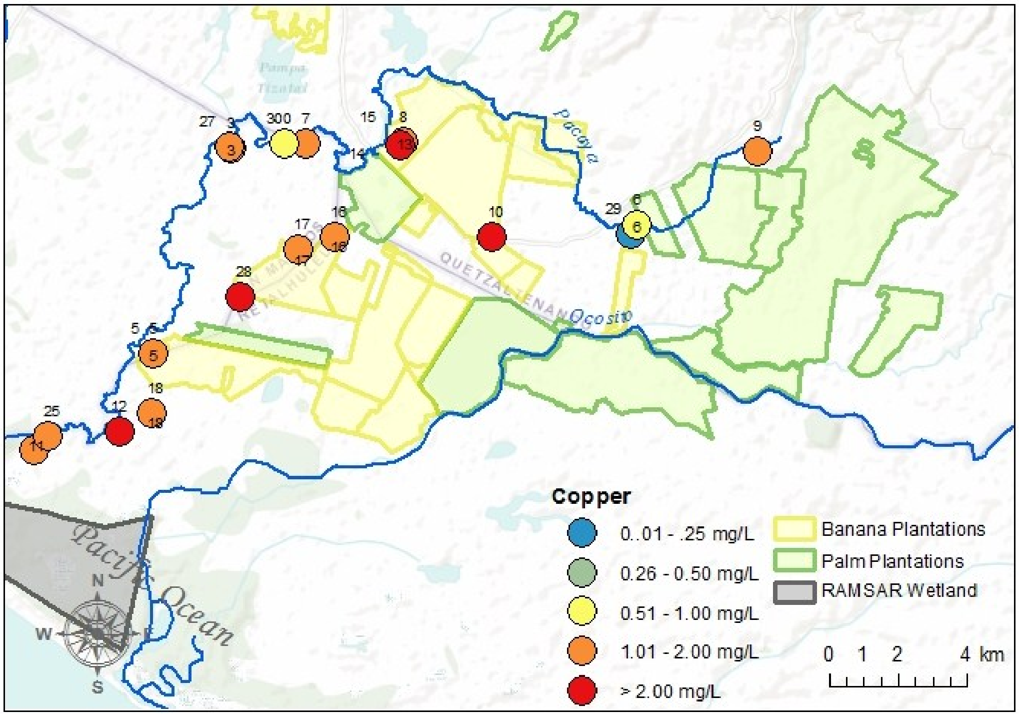


Figure 4.4. Dry Season locations and copper values.

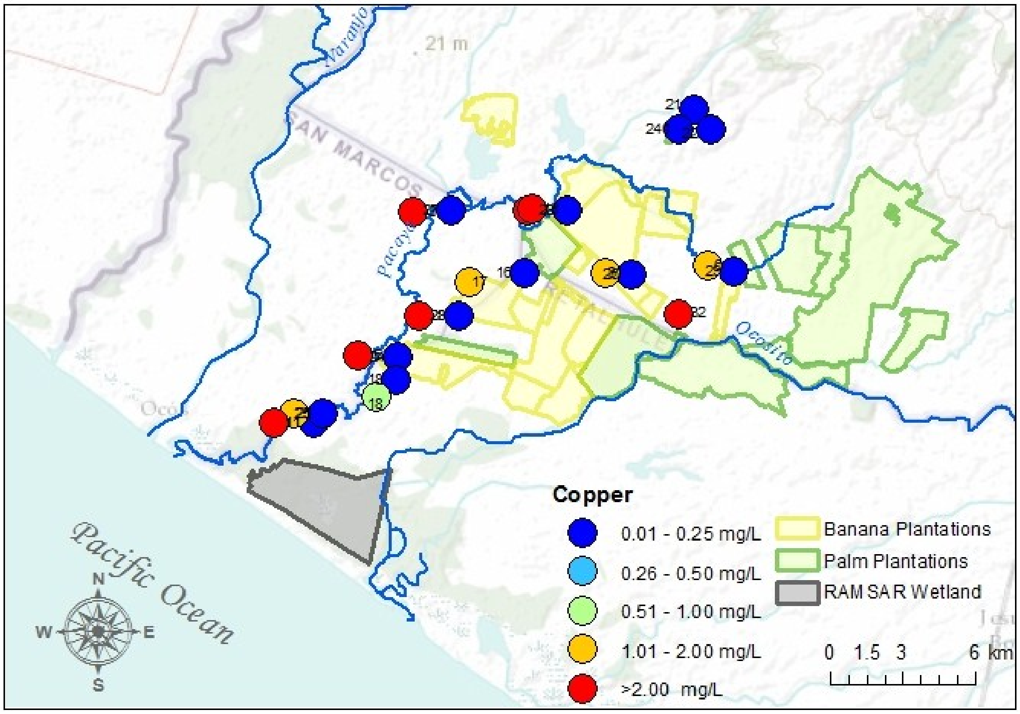


Figure 4.5. Wet Season locations and copper values.

<u>Chloride</u>

Chlorides in drinking water can originate from natural sources, sewage and industrial effluent, urban runoff, and saline intrusion. According to the WHO, concentrations in excess of 250 mg/L are the only standard and are detectable by taste. According to Washington State and EPA surface water standards, a one hour concentration of 860 mg/L is not to be exceeded more than once every three years on the average and a 4-day average concentration of 230 mg/L is not to be exceeded more than once every three years on the average. In regard to agricultural guidelines, high levels of chloride, above 140 mg/L in irrigated water can also impact plant growth, depending upon the tolerance of the specific crop (Tanji 1990, Fipps 2004). The maximum concentration without a loss of yield varies between crops. This concentration is 350 mg/L for beans, 525 mg/L for corn and 1,625 mg/L for cotton. The soil (clay) adsorbs the Cl, allowing the water to be pure for plant use. However, with time, the soil can only adsorb so much without making it available for the plant – thus becoming toxic for plants.

High levels in both dry and wet seasons were measured near the Reserva Natural Privada Manchon Guamuchal Wetland, levels exceeding both drinking water standards as well as for agricultural use (Figures 4.6 and 4.7). During the wet season, the level measured at a community well near banana and palm plantations exceeded drinking water standards.

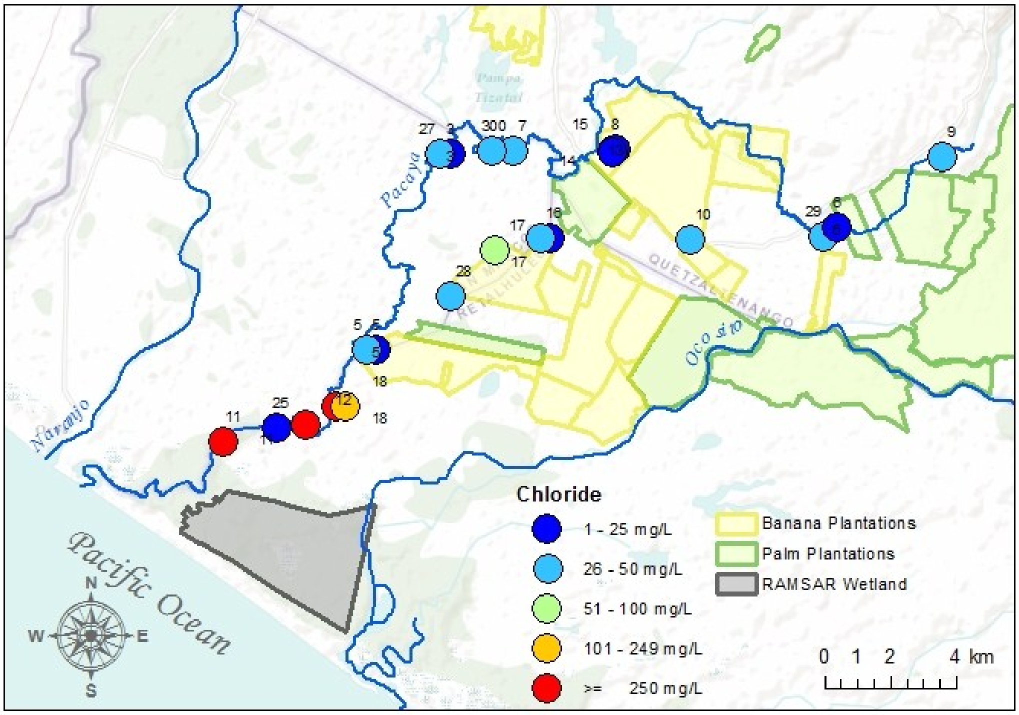


Figure 4.6. Dry Season locations and chloride values.

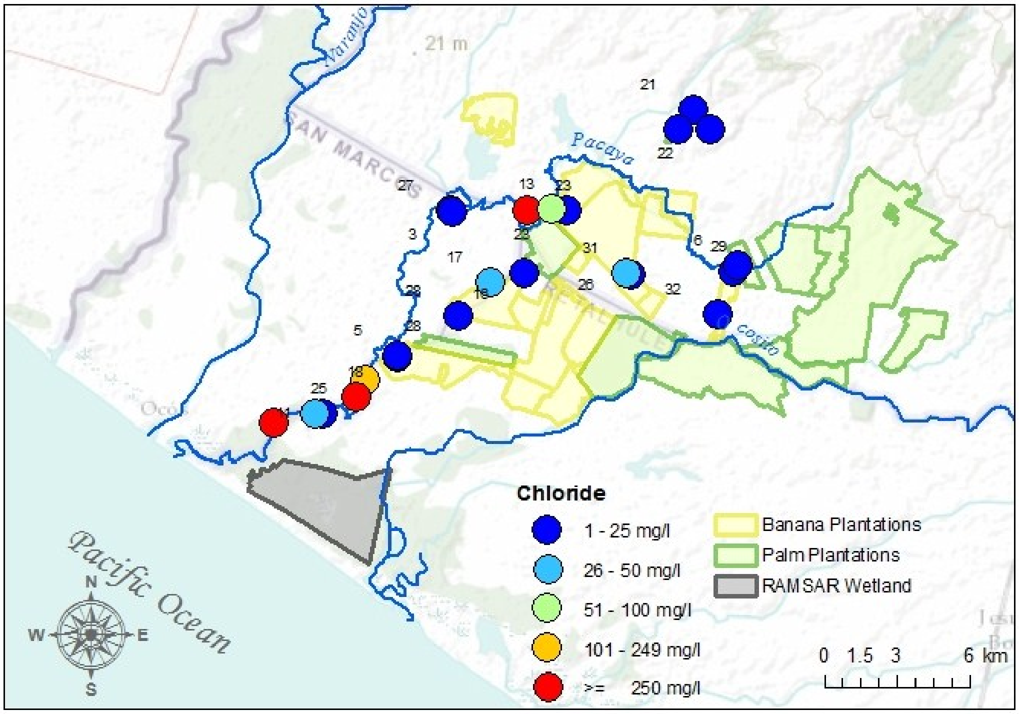


Figure 4.7. Wet Season locations and chloride values.

Dissolved Oxygen

The dissolved oxygen (DO) content of water is influenced by the source, water temperature, and chemical or biological processes occurring in nature (Uriate et al. 2011). There is no human-health-based standard, but low values are detrimental to aquatic life. Washington State's surface water standard is 6.5 mg/L. If dissolved oxygen levels in water decline below 5.0 mg/l, fish and other aquatic biota are stressed. Dissolved oxygen levels below 1-2 mg/l can result in large fish kills.

The low levels of DO explain the low levels of aquatic life in the rivers in the study area. Low levels of dissolved oxygen are the result of agricultural practices, such as channel modifications, which can decrease aeration and reduce riparian cover that results in temperature increases. In addition, land-use practices that release excess nutrients, organic matter, or other chemical contaminants reduce dissolved oxygen concentrations (Haygarth 2002). The majority of the samples were below the recommended level for both wet and dry seasons (Figures 4.8 and 4.9). This is a significant concern for the overall health of the ecosystem and provides evidence for some of the negative effects the plantations are having on the surrounding communities and ecosystems.

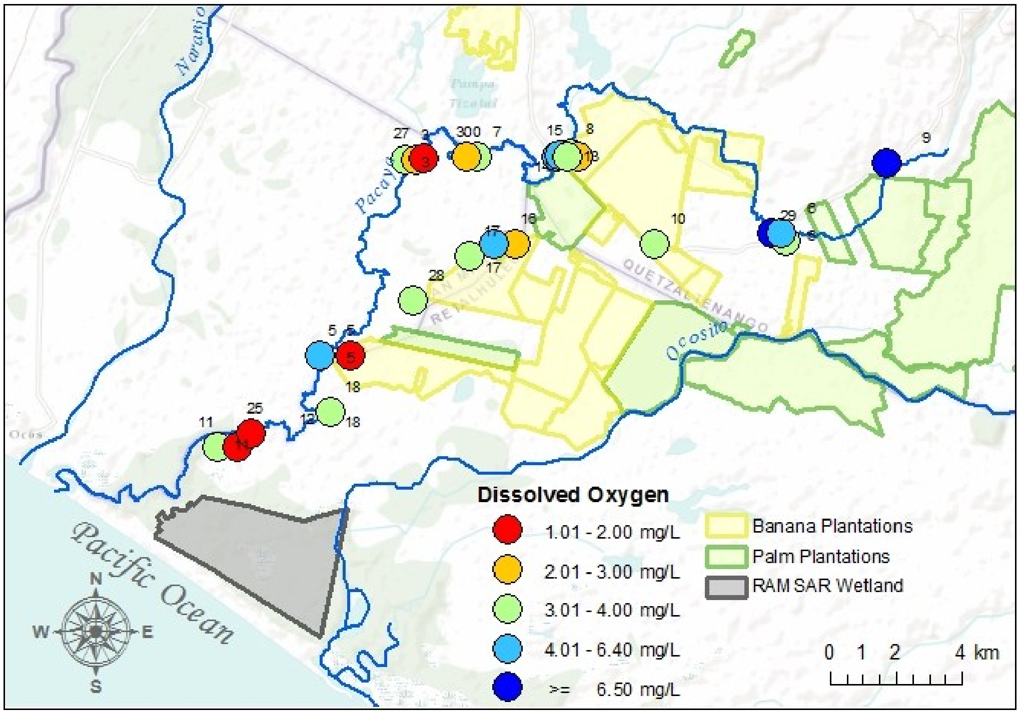


Figure 4.8. Dry Season locations and dissolved oxygen values.

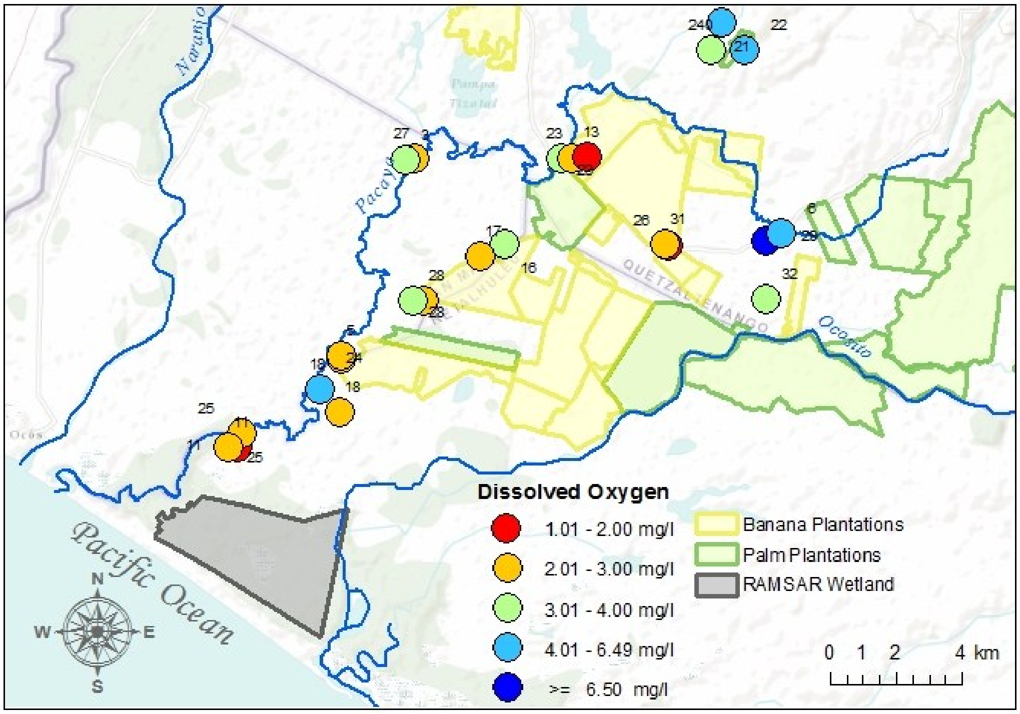


Figure 4.9. Wet Season locations and dissolved oxygen values.

Nutrients: Nitrates

Nitrogen is a plant nutrient and is applied to agricultural crops to maximize yield. Nitrate (NO_3) is found naturally in the environment and is part of the nitrogen cycle. Nitrite (NO_2) is not usually present in significant concentrations, except in a reducing environment, since nitrate is the most stable oxidation state. Nitrate carries a negative charge and this form is susceptible to leaching and runoff. Nitrate can reach both surface water and groundwater as a consequence of agricultural activity (including excess application of inorganic nitrogenous fertilizers and manures), from wastewater disposal, and from oxidation of nitrogenous waste products in human and animal excreta, including waste from septic tanks. A well-known effect of agricultural nitrate fertilization is its leaching from soils to water systems, leading to increased concentrations of nitrates in drinking water and downstream surface water systems (Matson et al. 1997). Surface water nitrate concentrations can change rapidly due to surface runoff of fertilizer, uptake by phytoplankton, and denitrification by bacteria. Groundwater concentrations generally show relatively slower changes. High nitrite consumption can result in methemoglobianemia, a consequence of the reaction of nitrites with hemoglobin in the red blood cells, resulting in oxygen-transport blockage. This can lead to cyanosis, which is referred to as “blue-baby syndrome.” For bottle-fed infants, drinking water can be the major external source of exposure to nitrates and nitrite. The WHO guidelines for nitrates are 50 mg/L for short-term exposure, 3 mg/L for short-term nitrite, and 0.2 mg/L long-term exposure for nitrate. Furthermore, the sum of the ratios of the concentration of each to its guideline value should not exceed 1.

NO_3 levels that exceed 45 mg/L in water that is used for irrigation may cause growth problems in crops and result in over-fertilization (Bauder et al. 1986). Many of the sites tested (Figures 4.10 and 4.11) had values that were all beyond the limits of the testing equipment, well above WHO guidelines. It is unclear if the values were accurate or if there was a problem with the testing equipment.

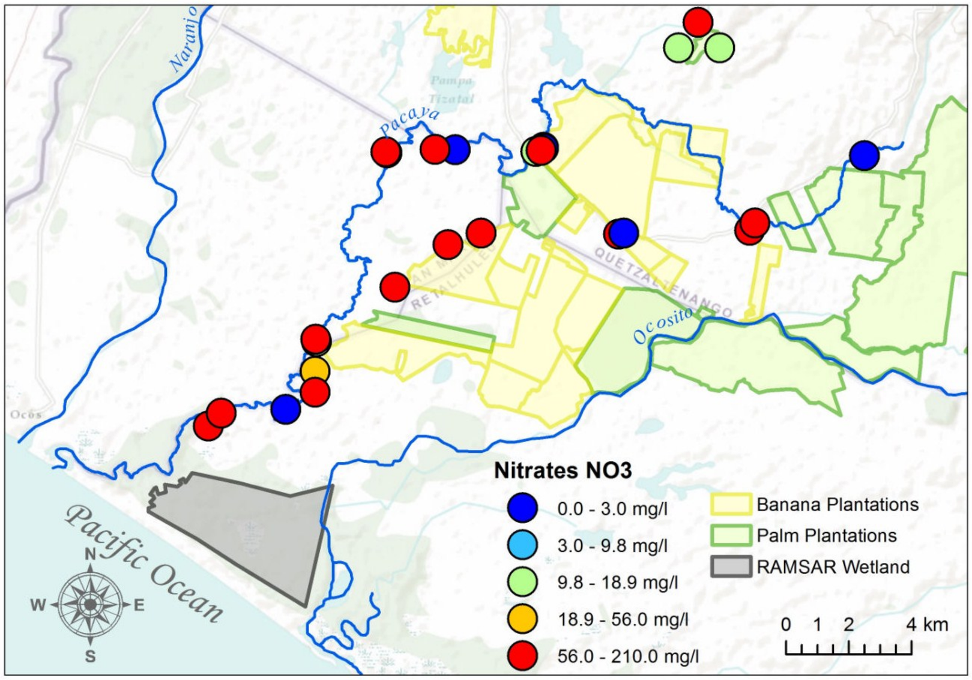


Figure 4.10. Dry Season locations and nitrate values.

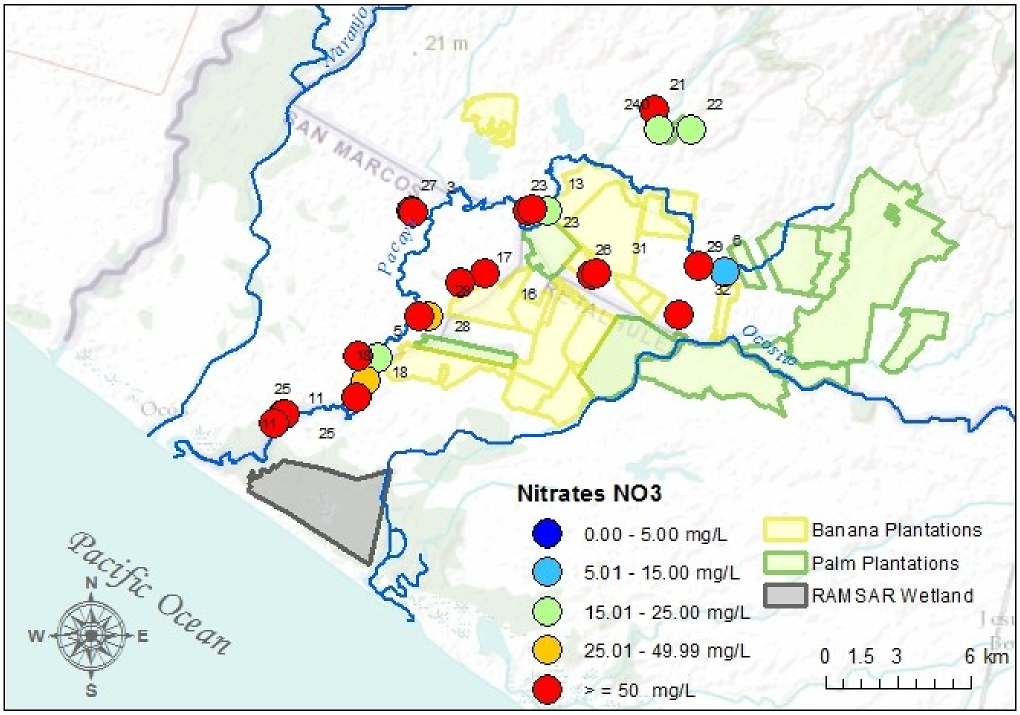


Figure 4.11. Wet Season locations and nitrate values.

Nutrients: Nitrites

Nitrite is an intermediary product in the process of nitrification, and typically it has a short half-life, although in high temperatures and poor aeration, NO_2 can accumulate. High NO_3, and pH levels >7.5 lead to NO_2 accumulation and leaching. NO_2 can be very toxic to aquatic organisms and the European Economic Community has set a maximum stream level to protect salmonoids at 9 micrograms per liter (Chapman and Kimstach 1996). The average N-NO_2 concentration for unpolluted rivers is 1.5 µg/L (Meybeck 1982). WHO guidelines for exposure in drinking water are 3mg/L for short-term exposure, and 0.2 mg/L for long-term exposure (WHO 2007). The nitrite levels detected are not dangerous for long term exposure in adults, but if babies are exposed to these levels for extended periods of time, there are major health concerns. Additional dangers are associated with the combination of nitrites and nitrates; each substance in isolation represents certain dangers, but they should also be considered in combination. As noted above, the WHO guidelines state that the sum of the ratios of each concentration to its guideline value should not exceed 1. This guideline exists in case each concentration was at least half of the guideline value due to the negative effects of combined nitrate/nitrite values.

The nitrite values measured, like the nitrate concentrations, are not considered to be quantitatively reliable, but they are thought to be above WHO standards. The highest values are adjacent to plantations (Figures 4.12 and 4.13).

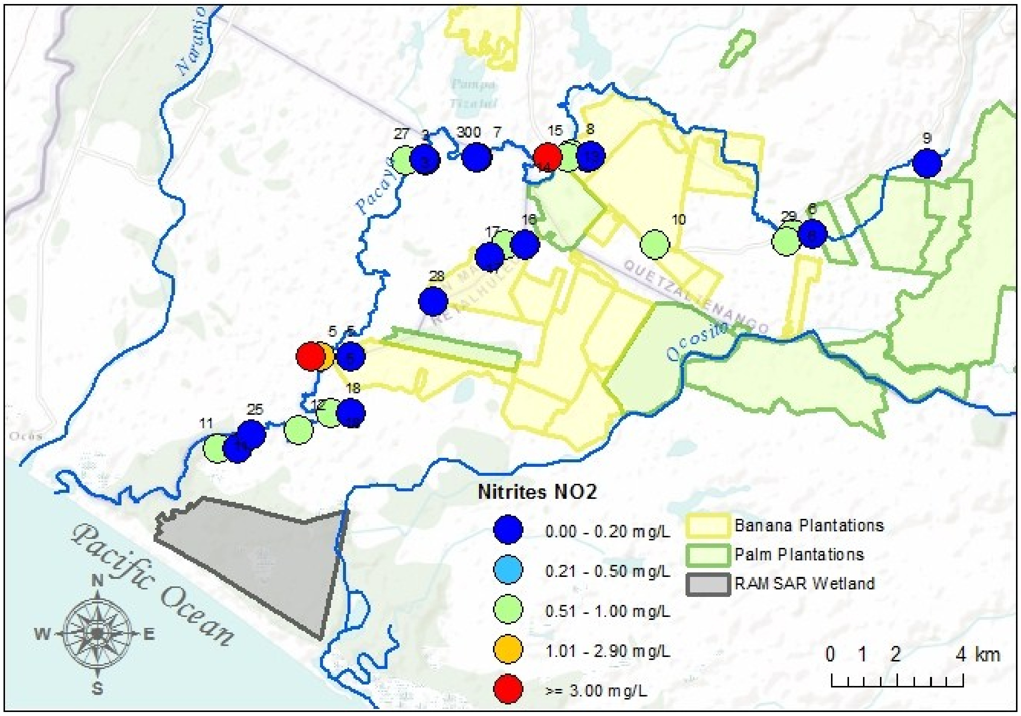


Figure 4.12. Dry Season locations and nitrite values.

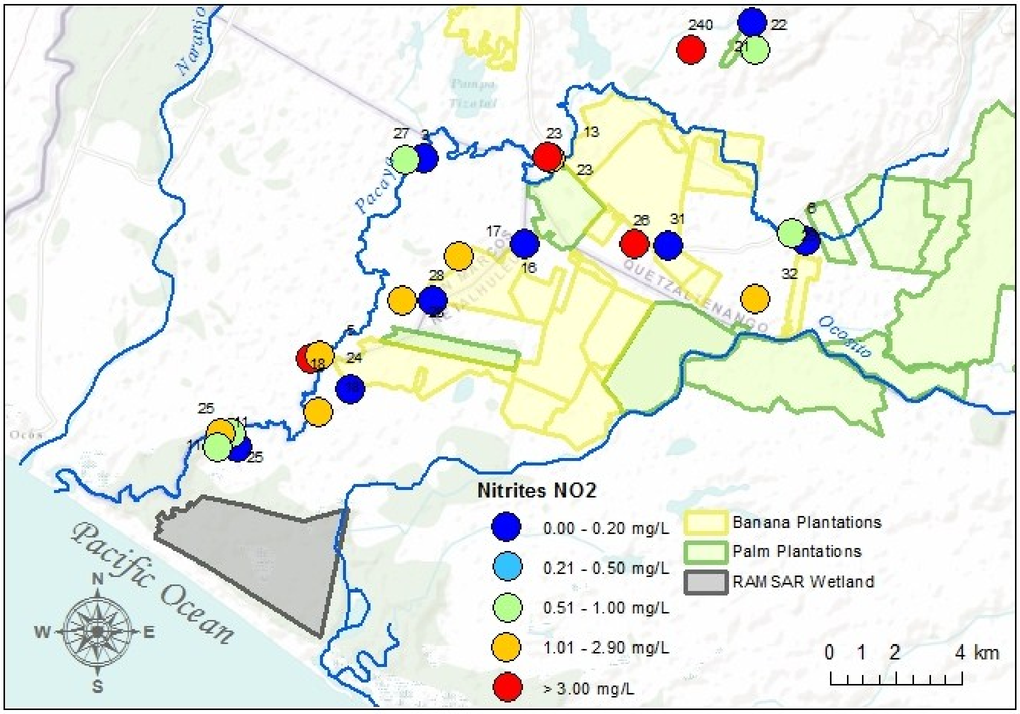


Figure 4.13. Wet Season locations and nitrite values.

Nutrients: Phosphate

Inputs of phosphorus as a result of excess fertilization are a widespread problem in rivers, lakes, estuaries, and coastal oceans. This over-enrichment causes eutrophication problems in rivers, estuaries, and lakes. The result is aquatic toxic algal blooms, loss of oxygen, fish kills, and loss of biodiversity. Eutrophication can lower the levels of dissolved oxygen in the water and can render the water uninhabitable by many aquatic organisms. Phosphorus generally does not occur as an element but as compounds (phosphates) and is often the limiting factor that determines the level of eutrophication that occurs. Aquatic ecosystems are degraded and the use of water for drinking and agriculture is impacted (Carpenter et al. 1998b). Phosphorus in water is not considered to be directly toxic to humans and animals; therefore, no drinking water standards have been established for P by the WHO or EPA, although the European Community standard is 5 mg/L.

(U.S. EPA 1990, Chapman and Kimstach 1996). Any toxicity caused by P in freshwaters is indirect because toxic algal blooms or anoxic conditions are stimulated by P pollution.

In freshwater, phosphorus is typically found in the phosphate (PO_4) form. High phosphate concentrations indicate high total phosphorus concentrations, which typify the water's trophic state. A body of water with concentrations of total phosphorus from 0-.12 mg/L is oligotrophic, from .012-.024 mg/L is mesotrophic, .024-.096 mg/L is eutrophic, and from .096- 0.384+ µg/L is hypereutrophic (Sharpley 1994, Chapman and Kimstach 1996).

Many samples tested showed high levels of phosphate and are considered hyper-eutrophic for both wet and dry seasons (Figures 4.14 and 4.15).

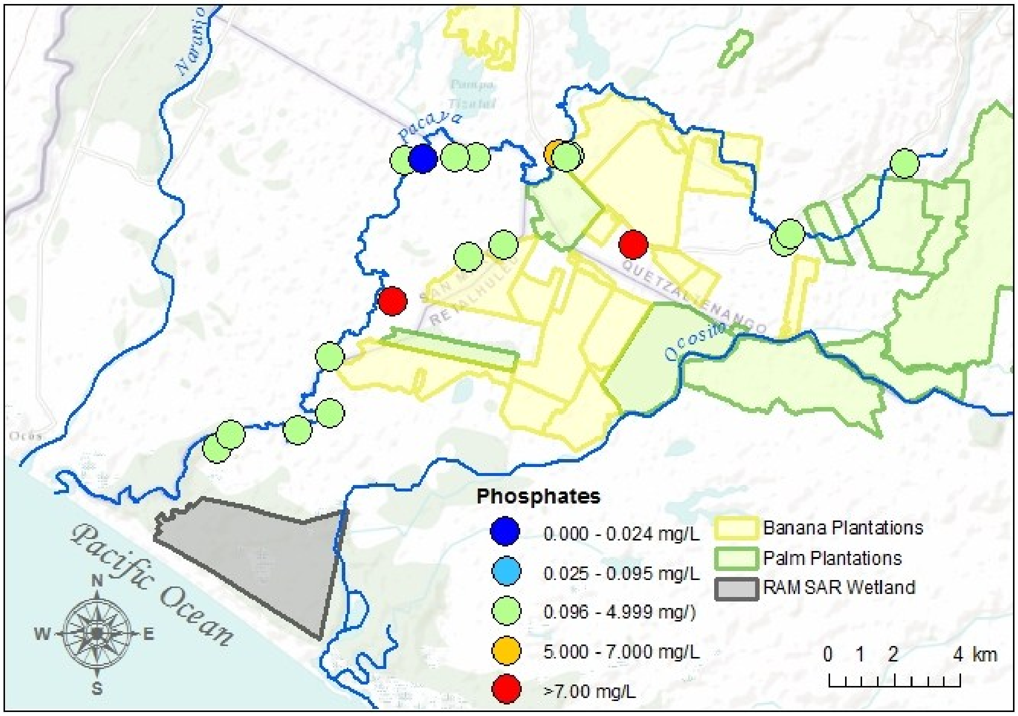


Figure 4.14. Dry Season locations and phosphate values.

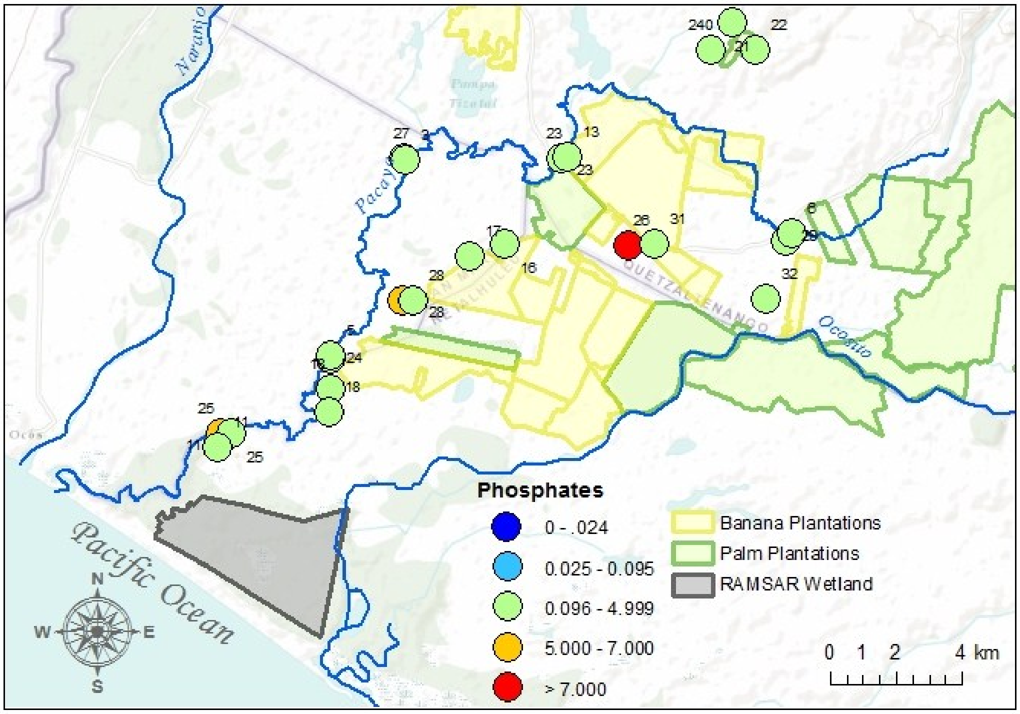


Figure 4.15. Wet Season locations and phosphate values.

General Parameters: pH

pH is one of the most important operational water quality parameters, with the commonly required optimum pH in the range of 6.5–8.5. That range corresponds to Washington State's surface water standards, with a human-caused variation, within the above range, of less than 0.2 units (Washington State Department of Ecology). The WHO maximum contaminant level (MCL) is also 6.5-8.5 (World Health Organization 2004) .Although there are no health-based guidelines, values above and below the above range can affect fish development and reproduction (Boyd 1982). Although the pH of most natural waters is between 6.0 and 8.5m, lower values can occur in waters high in organic content; higher values, in eutrophic waters, groundwater brines and salt lakes. pH readings above 8.5 can be caused by high bicarbonate concentrations. Alkaline water can intensify the impact of high sodium absorption ratio (SAR) water on sodic soil conditions, creating more problems with salinity if this water is used for irrigation (Bauder et al. 1986). The level of pH also influences the release of phosphorus from sediment; it increases as pH increases, up to 9.5 (Baldwin et al.2002). pH in the study area is the highest in localities to the north and adjacent to palm plantations for the dry season, but also near the wetlands during the wet season (Figures 4.16 and 4.17).

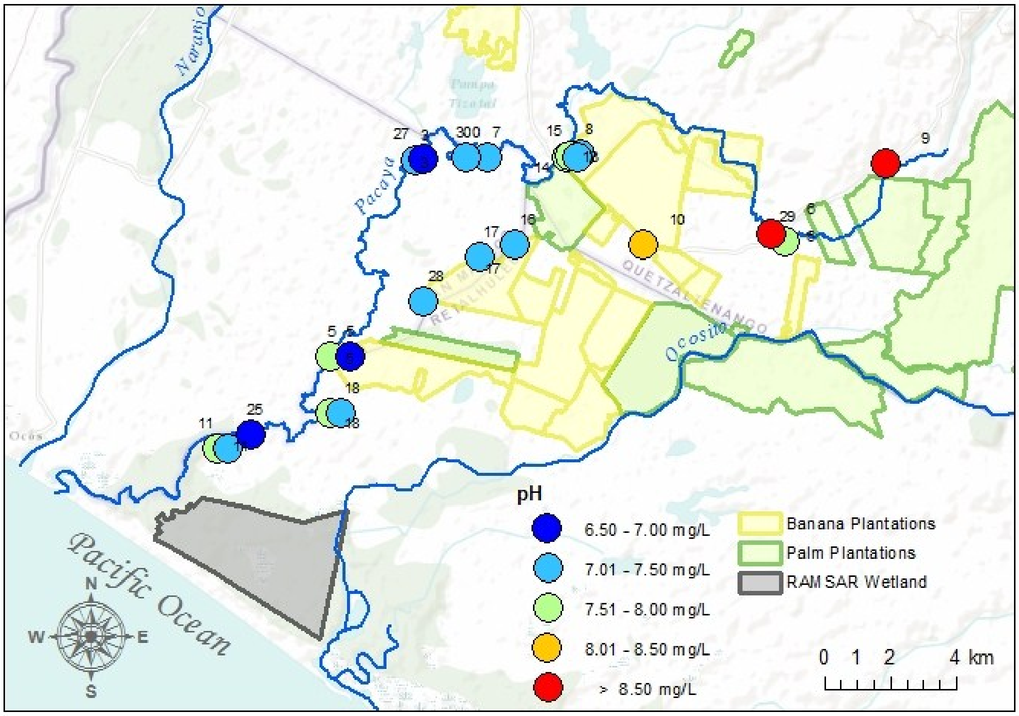


Figure 4.16. Dry Season locations and pH values.

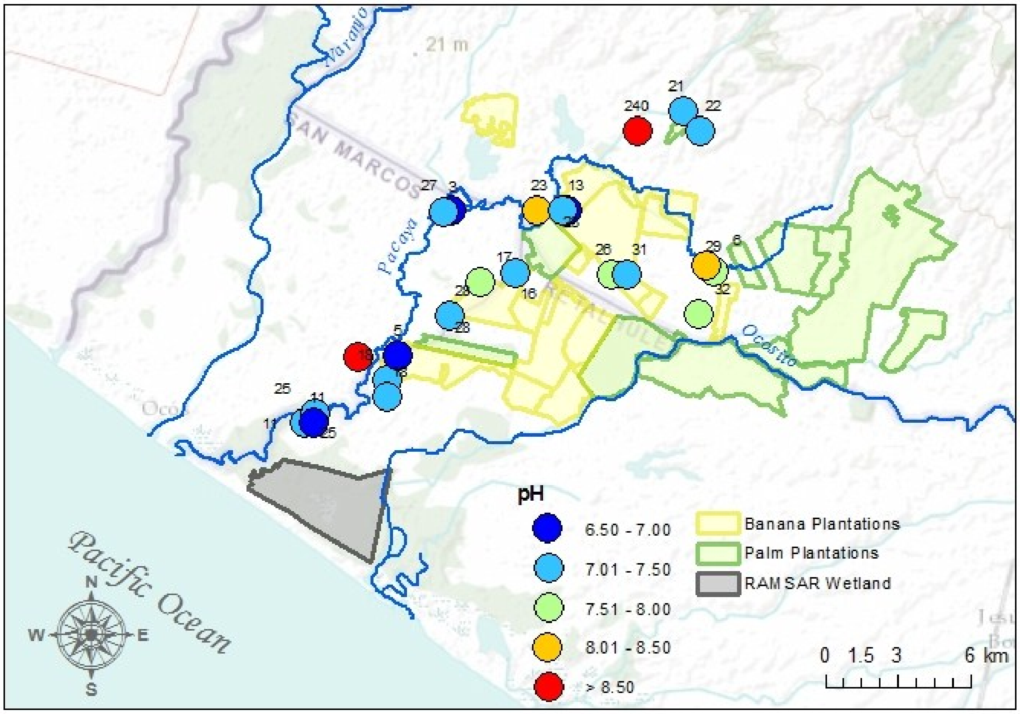


Figure 4.17. Wet Season locations and pH values.

Salinity (Sodium) and Conductivity

The concentration of sodium in surface waters is dependent upon geology, wastewater, and the amount of agricultural irrigation. Sea water intrusion can cause high levels in coastal and downstream surface water, especially during dry season. These sources can also affect ground water. The WHO standards recommend drinking water levels not to exceed 200 mg/L or 0.2 ppt (Chapman and Kimstach 1996). Fresh water in rivers commonly has a salinity of 0.5 ppt or less, and drinking water is typically 0.1 ppt or less.

The increased levels of salts disrupt the life cycle of freshwater aquatic organisms, and some cannot live in these waters. Water salinity can reduce crop yields on irrigated land because increased sodium levels can degrade the soil chemistry and structure, thereby restricting water movement and affecting plant growth (Lee and Howitt 1996).

A guideline for crop productivity and salinity can be measured by electrical conductivity. A high measure results in the inability of the plant to compete with ions in the soil solution or water causing a physiological drought. As the conductivity increases, the usable plant water decreases. Plant yield reductions vary, given the crop being produced, although generally less than 75 dS/cm has no effect; greater than 75 and less than 150 has some effect; greater than 150-300 has a moderate effect, and a severe effect results from values greater than 300 (Bauder et al 1986; Chapman and Kimstach 1996). Conductivity and salinity measurements were very high in the area adjacent to the protected wetland, and conductivity measurements were in levels of concern throughout the study area (Figures 4.20 and 4.21).

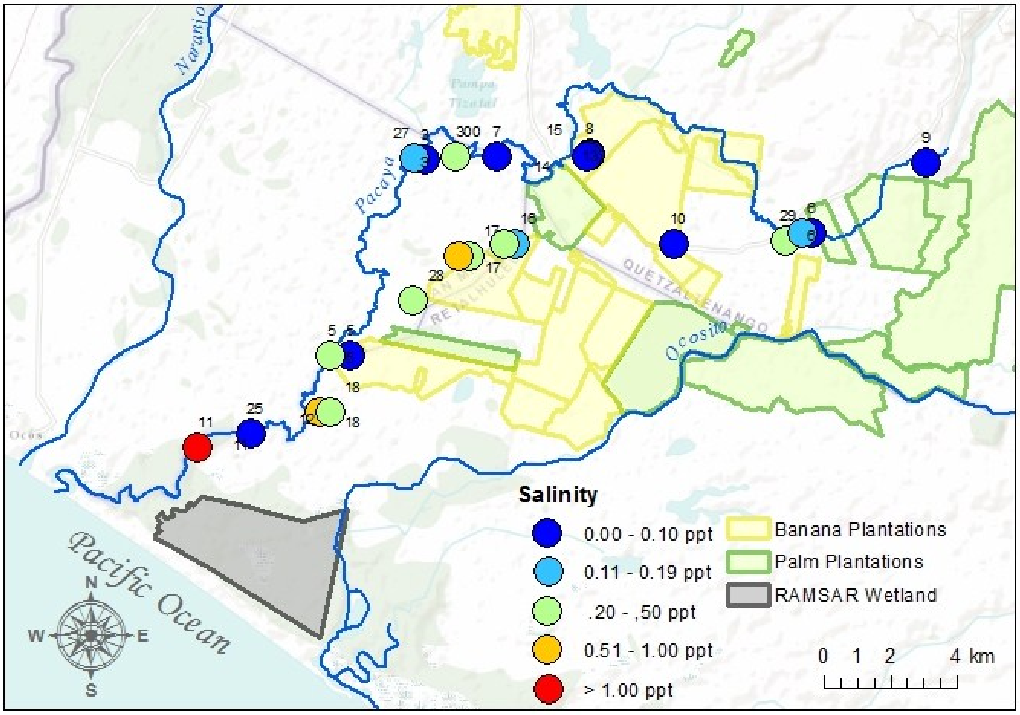


Figure 4.18. Dry Season locations and salinity values.

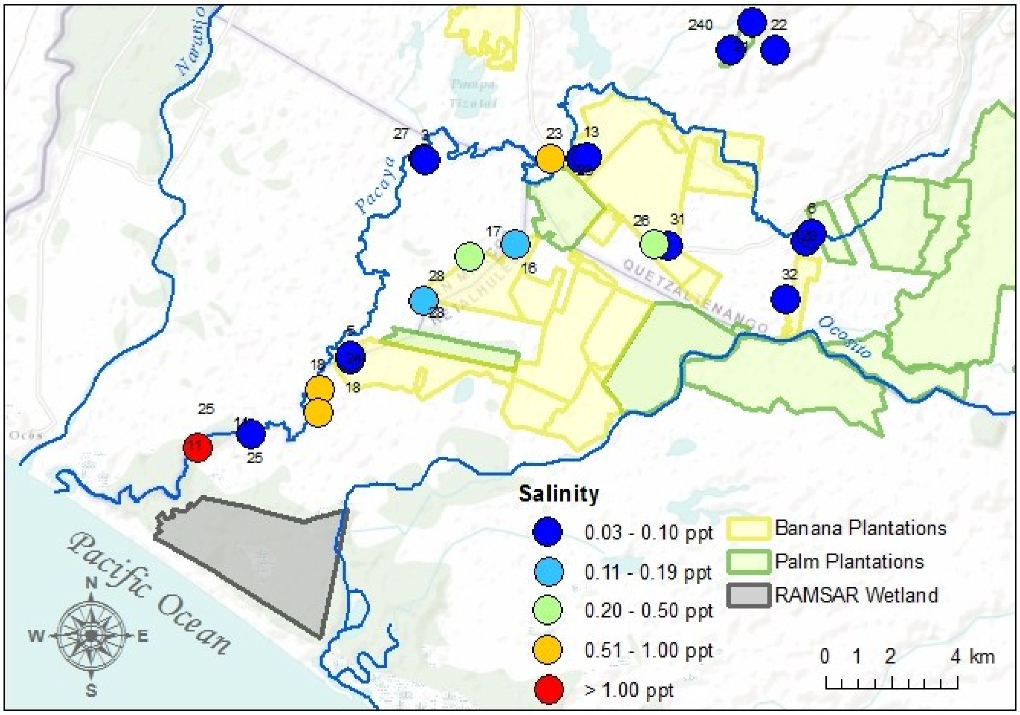


Figure 4.19. Wet Season locations and salinity values.

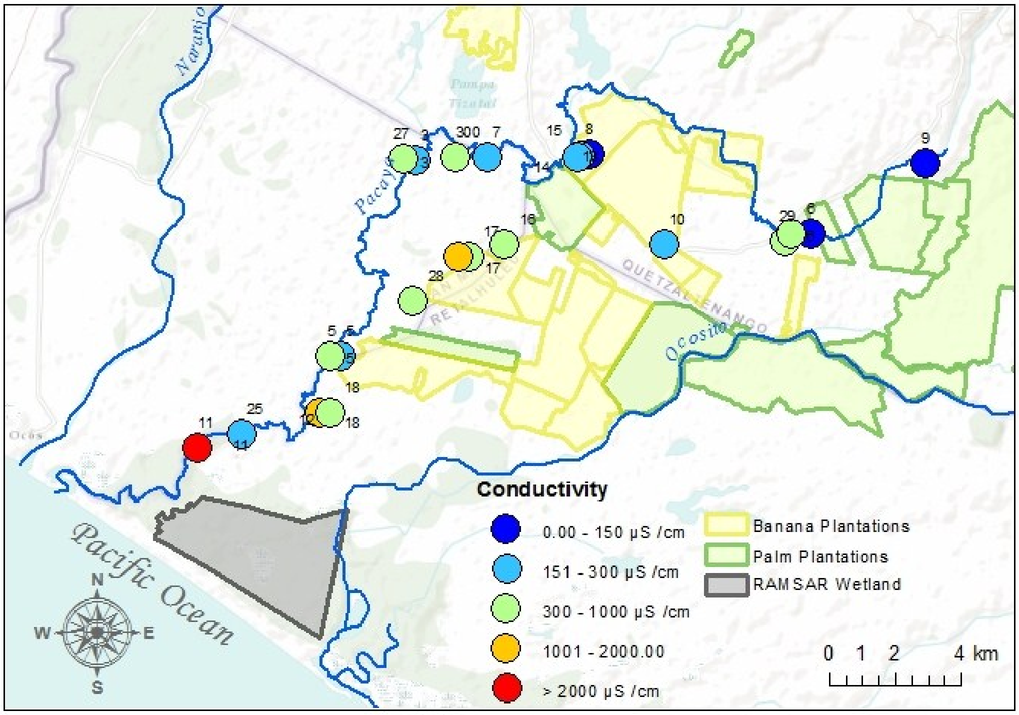


Figure 4.20. Dry Season locations and conductivity values.

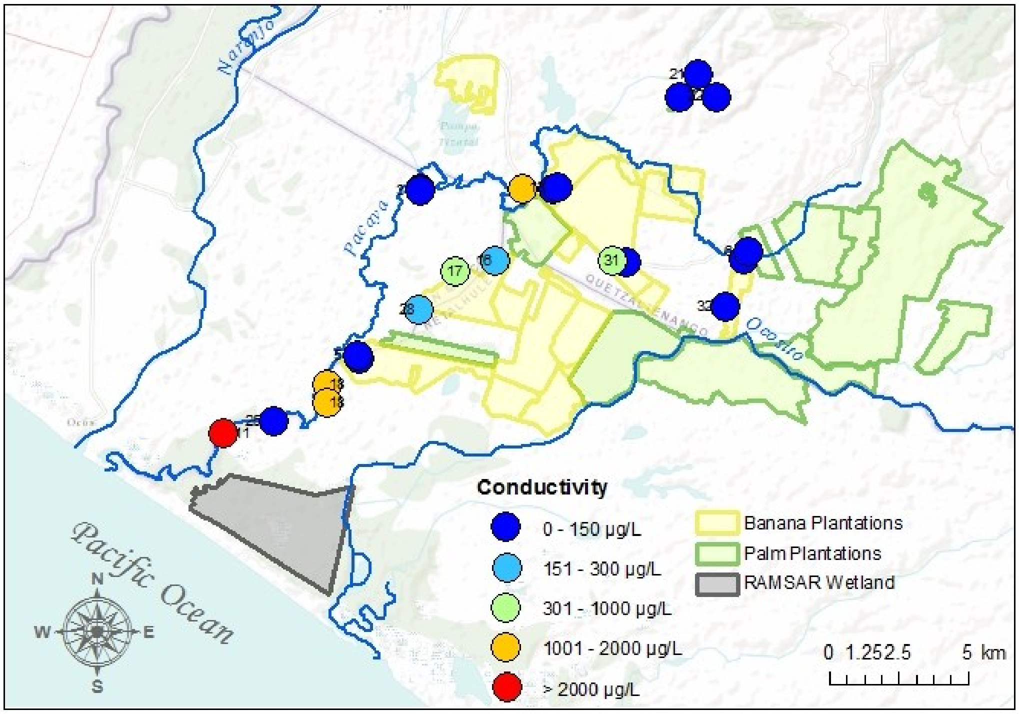


Figure 4.21. Wet Season locations and conductivity values.

Total Dissolved Solids

Total dissolved solids (TDS) in surface and drinking water originate from natural sources, sewage, urban runoff, and industrial wastewater. TDS consist of inorganic salts (primarily calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and small amounts of organic matter. A certain level of these ions in water is necessary for aquatic life. However, changes in TDS concentrations can be harmful because the density of the water determines the flow of water into and out of an organism's cells (Mitchell and Stapp 1994). High concentrations of TDS may also reduce water clarity and may contain toxic compounds and heavy metals. They may cause an increase in water temperature and reduction in dissolved oxygen (California State Water Resources, 2001).

TDS is used to estimate the quality of drinking water because it represents the amount of ions in the water. Water with high TDS often has a bad taste and/or high water hardness.

Washington State's surface water standards designate that water with a TDS of less than 600 mg/L is palatable and drinking water becomes significantly unpalatable at TDS levels greater than 1000 mg/L. The WHO standard is 1000 mg/L (Chapman and Kimstach 1996). In the study area, high TDS levels are adjacent to the wetland and banana plantations (Figures 4.22 and 4.23).

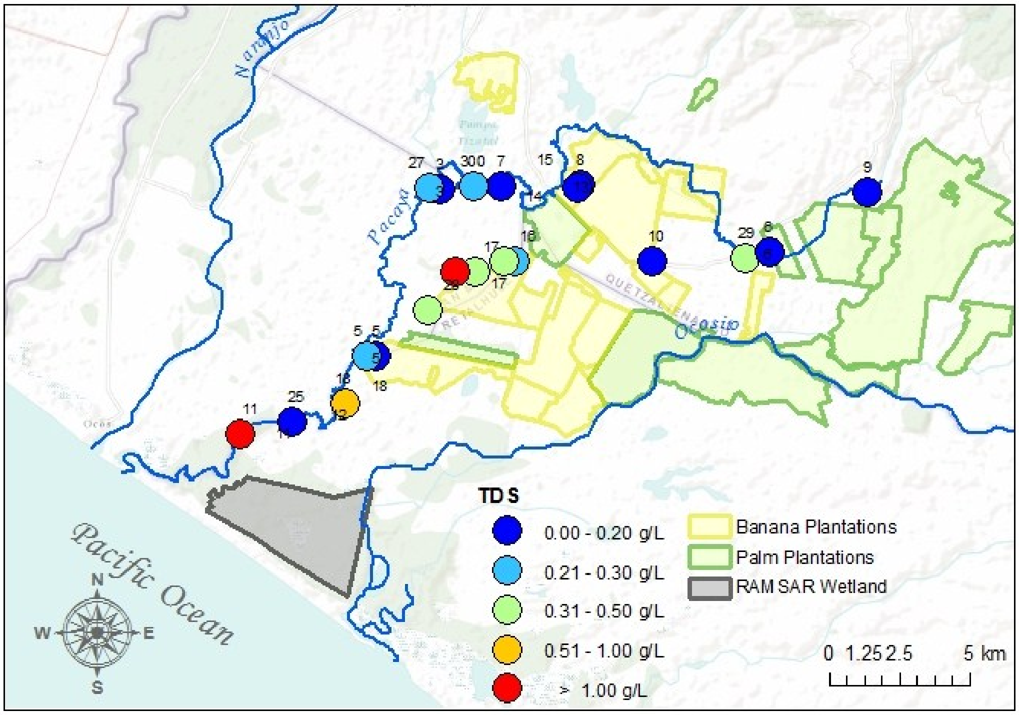


Figure 4.22. Dry Season locations and TDS values.

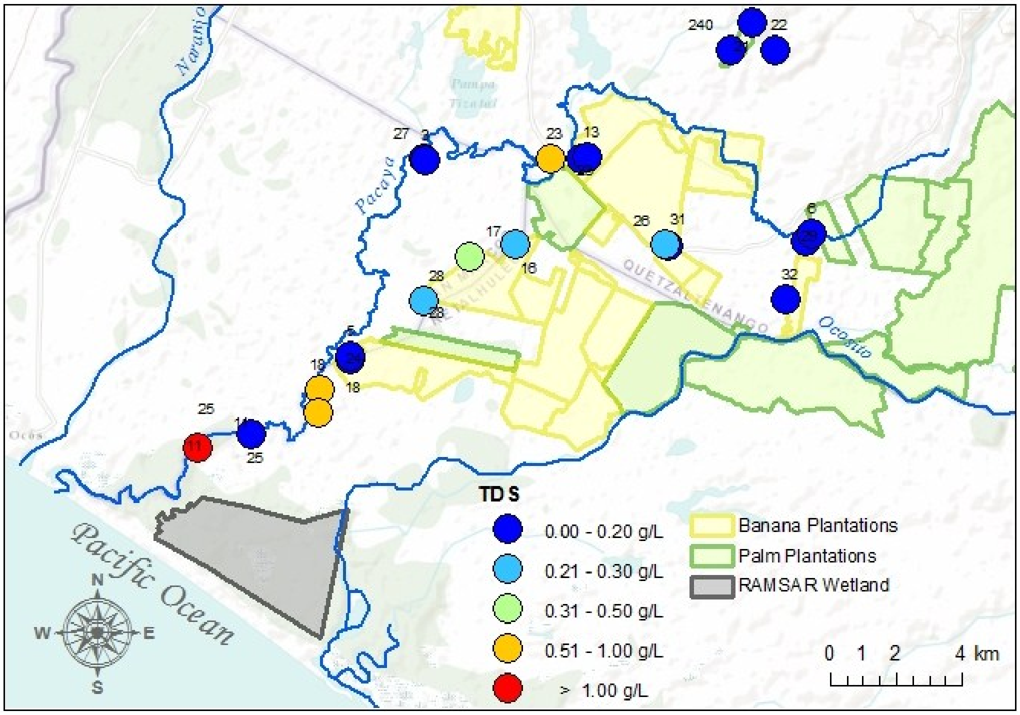


Figure 4.23. Wet Season locations and TDS values.

Measurements of Suspended Sediment (Solids)

Total Suspended Solids (TSS)

Excessive erosion, transportation, and deposition of both suspended and bed-load sediments in surface waters are a major form of pollution, resulting in extensive water-quality problems. Total Suspended solids (TSS) may include a wide variety of material, such as silt, decaying plant and animal matter, industrial wastes, and sewage, and high concentrations of suspended solids can cause many problems for stream health and aquatic life. High levels of TSS can block light from reaching submerged vegetation, resulting in their death. As the plants decompose, bacteria will consume even more oxygen from the water. High TSS can also cause an increase in surface water temperature, because the suspended particles absorb heat from sunlight, resulting in a decrease in dissolved oxygen. (Mitchell and Stapp 1994; KanCRN 2012)

There is no health-based or surface water quality guideline proposed for suspended solids. However, the amount of solids suspended in water is significant because pathogens can adhere to these solids or the pathogens themselves can form clumps. High values were scattered through the study area during the wet season, with high values during the dry season adjacent to banana plantations (Figures 4.24 and 4.25).

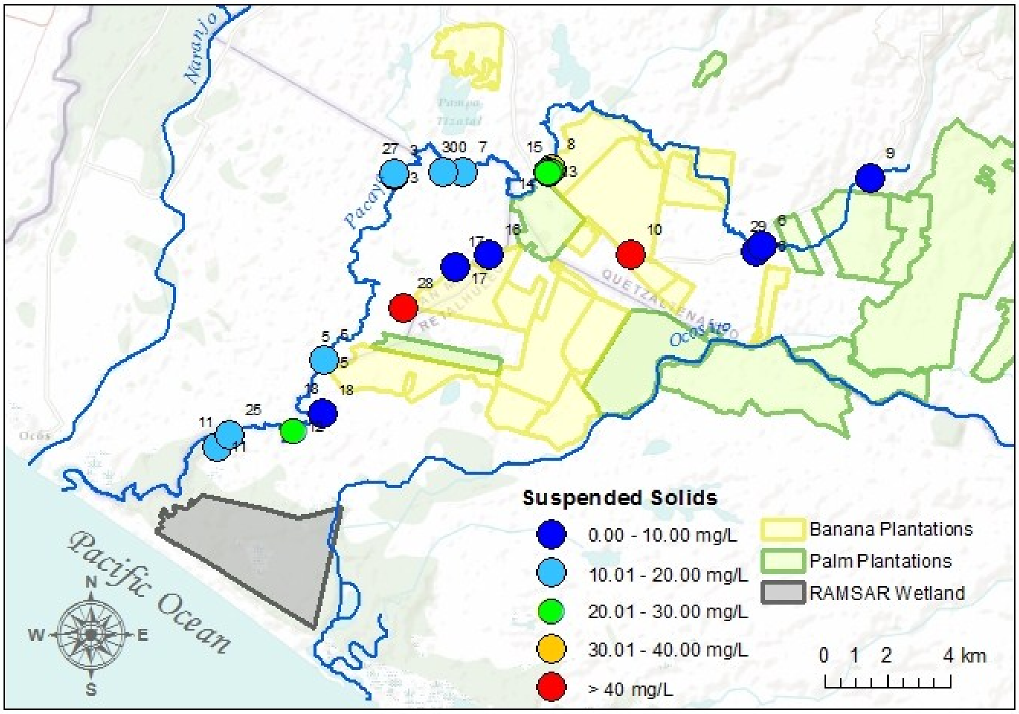


Figure 4.24. Dry Season locations and TSS values.

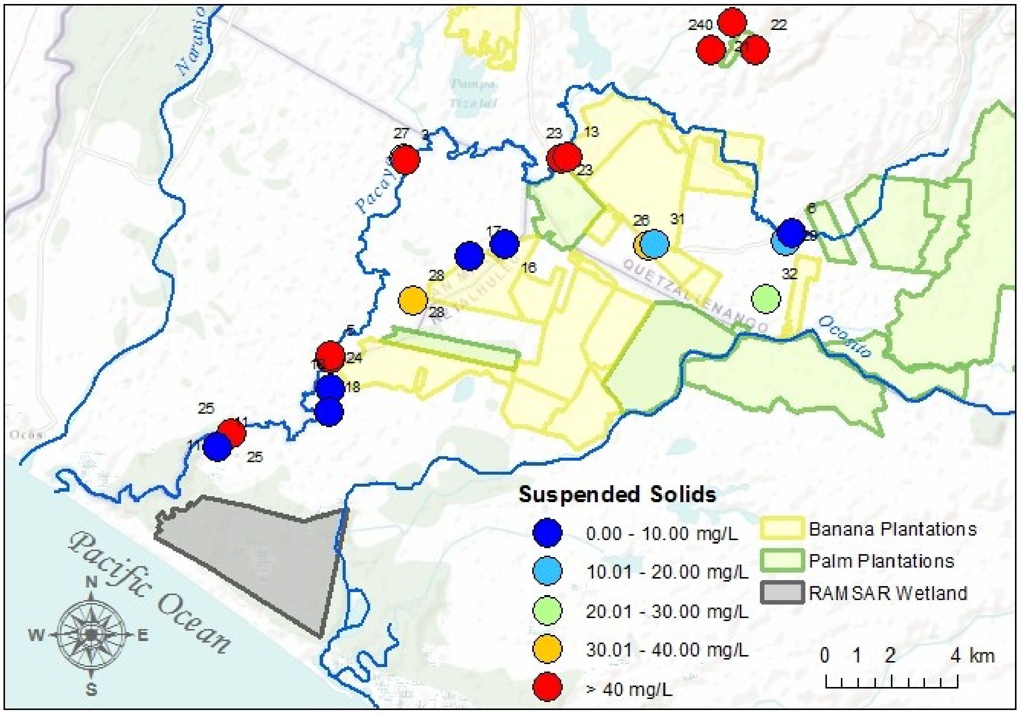


Figure 4.25. Wet Season locations and TSS values.

<u>Turbidity</u>

Turbidity is caused by particulate matter that has not settled and is a measure of light penetration. This measure is positively correlated with sediment erosion and in-stream production of sediment (Eaton and Franson 2005). There is no health-based guideline for turbidity, but a median turbidity should be below 0.1 Nephelometric Turbidity Units (NTU). According to Washington State's surface water standards, water with a 10 NTU increase over background when the background is 50 NTU or less, or a 20 percent increase in turbidity when the background turbidity is more than 50 NTU, is not permitted (Washington State Department of Ecology). The WHO has a standard of 5 NTU's. Levels can be increased by the presence of organic-matter pollution, other effluents, or runoff with high suspended matter. Particulates can protect microorganisms from the effects of disinfection and can stimulate bacterial growth. In all cases turbidity must be low in order for disinfection to be effective.

Nearly all samples in the study area demonstrated turbidity above the recommended WHO level (Figures 4.26 and 2.27).

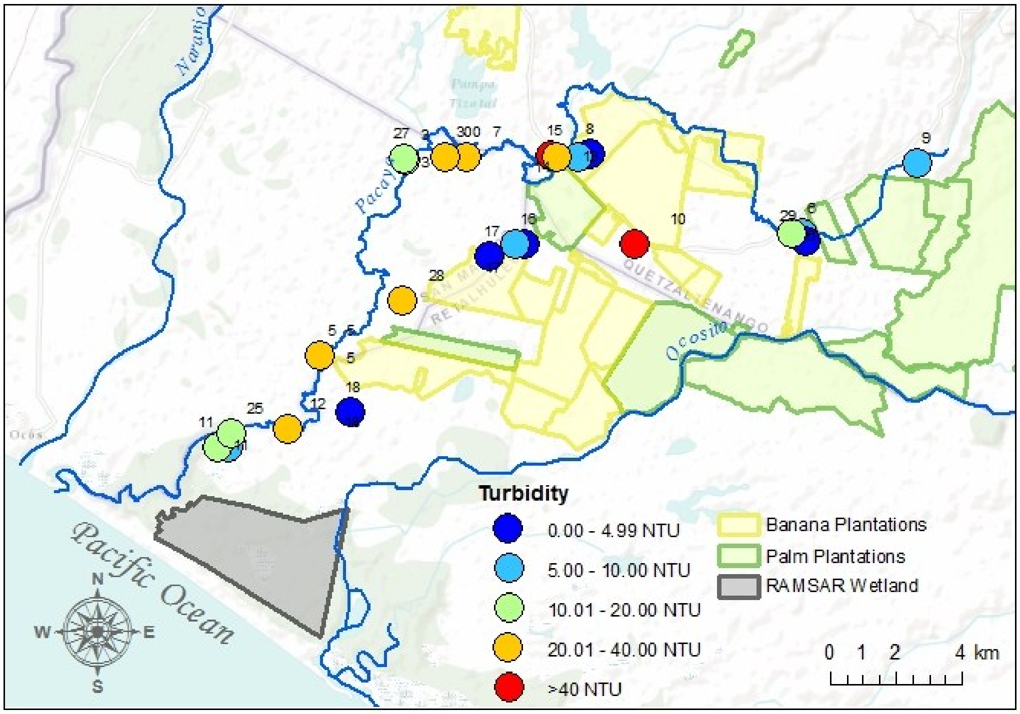


Figure 4.26. Dry Season locations and turbidity values.

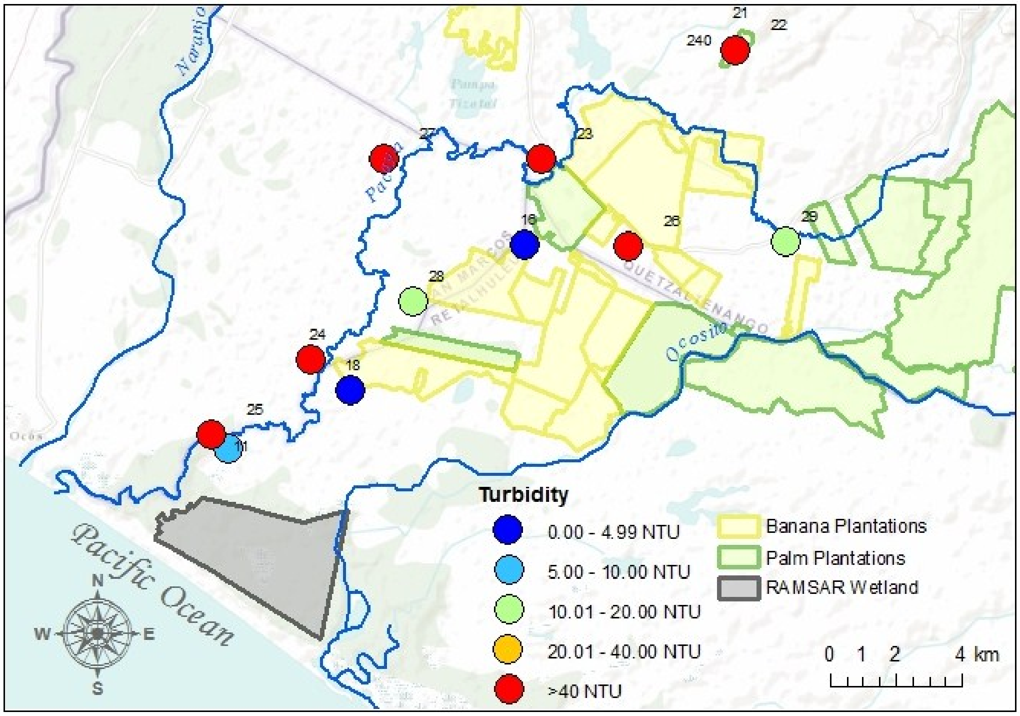


Figure 4.27. Wet Season locations and turbidity values.

Data Analysis

Values of water-quality parameters are separated according to their collection periods into wet and dry seasons. As shown in Table 4.3, mean values overall are similar for some parameters, i.e., salinity, dissolved oxygen, and total dissolved solids (TDS). In order to compare the variability of different data sets, a coefficient of variation was calculated. Many parameters have coefficient of variation greater than 1, indicating high relative variability (Zar 1999).

Table 4.3. Water Quality Statistics Wet Season

	Mean	**STD**	**Max**	**Min**	**CV**
Arsenic (µg/L)	1.23	1.95	8.42	0.01	1.58
Chloride (mg/L)	136.16	329.40	1372.37	2.70	2.42
Conductivity (µS /cm)	1301.79	3384.42	15414.00	67.70	2.60
Copper (mg/L)	2.24	3.76	14.94	0.01	1.68
DO (mg/L)	3.24	1.47	7.06	0.54	0.45
Nitrates (mg/L)	150.10	81.83	200.00	9.84	0.55
Nitrites (mg/L)	1.37	1.18	4.00	0.00	0.86
Phosphates (mg/L)	2.28	2.92	14.30	0.40	1.28
pH	7.54	0.85	10.38	6.50	0.11
Salinity (ppt)	0.66	1.83	8.56	0.03	2.80
SS (mg/L)	45.40	47.59	195.00	0.00	1.05
TDS (mg/L)	0.78	2.07	9.60	0.04	2.65
Turbidity (NTU)	60.41	60.45	238.00	0.32	1.00

Table 4.4. Water Quality Statistics Dry Season

	Mean	**STD**	**Max**	**Min**	**CV**
Arsenic (µg/L)	4.15	8.86	47.61	0.15	2.13
Chloride (mg/L)	87.04	192.50	1000.00	4.50	2.21
Conductivity (µS /cm)	591.69	662.44	2500.00	127.10	1.12
Copper (mg/L)	3.08	5.76	25.00	0.27	1.87
DO (mg/L)	3.93	1.79	8.19	1.25	0.45
Nitrates (mg/L)	85.94	98.03	200.00	0.80	1.14
Nitrites (mg/L)	2.38	7.10	30.50	0.00	2.99
Phosphates (mg/L)	3.07	2.71	14.50	0.00	0.88
pH	7.56	0.52	8.86	6.76	0.07
Salinity (ppt)	0.64	2.19	11.94	0.05	3.42
SS (mg/L)	13.28	11.56	50.00	0.00	0.87
TDS (mg/L)	0.77	2.39	13.05	0.07	3.12
Turbidity (NTU)	14.60	13.90	65.10	0.21	0.95

Correlation Analysis

A correlation matrix of the parameters was calculated for the entire cycle, including wet and dry seasons (Tables 4.5 and 4.6). For the wet season, high and positive values are between salinity, conductivity, TDS, and chloride. There is also a positive correlation between arsenic, copper and chloride. During the dry season, conductivity, chloride and salinity have lower, but still significant, values. There is a positive relationship between chloride and conductivity as well as chloride and copper. Both arsenic and copper have high positive relationship to salinity. TDS was highly positively correlated to arsenic, copper and chloride, as well as to conductivity.

Table 4.5. Wet Season Correlation Matrix

	arsenic	*Copper*	*Chloride*	*Conductivity*	*Turbidity*	*SS*	*Phosphorus*	*pH*	*Nitrates*	*Nitrites*	*TDS*	*DO*	*Salinity*
Arsenic	1												
Copper	0.590153	1											
Chloride	0.578679	0.514339	1										
conductiv	0.284059	0.237262	0.885763	1									
Turbidity	-0.23702	0.221719	-0.30787	-0.3052725	1								
SS	-0.18972	0.227462	-0.27169	-0.2683044	0.981798	1							
Phosphor	-0.08224	-0.19279	-0.06449	-0.0526519	0.002935	-0.0494106	1						
pH	0.029865	-0.33334	-0.33469	-0.2603291	0.141252	0.17580142	0.14920544	1					
Nitrates	0.11127	0.374346	0.208518	0.18313671	-0.02111	-0.094357	-0.0623346	-0.58852	1				
Nitrites	0.373967	0.113461	-0.16603	-0.2444349	0.185184	0.1501806	-0.1423941	0.46522	-0.0557	1			
TDS	0.255939	0.212862	0.869115	0.99933026	-0.29927	-0.2633343	-0.0510021	-0.25344	0.180182	-0.24711	1		
DO	-0.23073	-0.16333	-0.34676	-0.408015	0.111892	0.17374057	-0.3828542	0.164807	-0.42399	-0.26778	-0.41001	1	
Salinity	0.235179	0.197448	0.855919	0.99795409	-0.28902	-0.253577	-0.0490753	-0.24401	0.177561	-0.24828	0.999561	-0.40949	1

Table 4.6. Dry Season Correlation Matrix

	arsenic	*Copper*	*CL*	*Conductivity*	*Turbidity*	*SS*	*hosphoru*	*pH*	*Nitrates*	*Nitrites*	*TDS*	*DO*	*Salinity*
arsenic	1												
Copper	0.772408	1											
CL	0.690895	0.903805	1										
Conductiv	0.438887	0.537858	0.792187	1									
Turbidity	-0.09889	-0.09571	-0.23909	-0.337524664	1								
SS	-0.13258	-0.03568	-0.19631	-0.363035831	0.818308	1							
Phosphor	0.040604	0.17534	0.021541	-0.174881032	0.73724	0.873853	1						
pH	-0.14136	0.09067	-0.00422	-0.166670158	-0.05202	-0.12785	-0.11963	1					
Nitrates	-0.13614	-0.03125	0.056184	0.319030467	-0.07591	-0.18307	-0.20393	-0.32571	1				
Nitrites	-0.19815	-0.00753	-0.08867	-0.131043552	0.277257	0.315712	0.275118	-0.2365	0.384921	1			
TDS	0.757802	0.980237	0.951051	0.675503277	-0.18019	-0.12921	0.090781	0.052716	0.043889	-0.06825	1		
DO	-0.23178	-0.05088	-0.16545	-0.323298745	0.06193	0.083014	-0.02815	0.813161	-0.46464	-0.25453	-0.10156	1	
Salinity	0.759682	0.984822	0.945027	0.65650383	-0.16578	-0.11147	0.108856	0.0655	0.023594	-0.06297	0.999161	-0.09114	1

Measurement Analysis By Sector

Water quality measurements were separated by their location along the river for the dry season and the wet season (Tables 4.7 and 4.8). The group title Upper Agriculture is comprised of the most northeast section of the river, the Middle Agriculture is those areas in the mid-section of the area. The adjacent-to-wetland area is comprised of water location points in the lower part of the river near the protected wetland. Statistics were calculted for each group of measurements to allow a comparison between groupings. For almost all values, water quality measurements increased along the gradient of the river, moving towards the ocean as these measurements tend to accumulate and settle particularly in the areas of low elevation.

While it is important to look at the mean, it is important to compare maximum, minimum and coefficient of variation (CV) values for each paramter. For an important parameter, nitrates, the middle grouping's mean values were highest for the wet season, compared to the area near the wetland being the highest. Water quality measurements for the wet season compared to the dry season were quite different. For example, arsenic and nitrite dry season mean values exceeded wet season values for all three regions possibly due to an increase in concentrations due to less water in the river system. Nitrates wet season values exceeded dry season values for all three regions as well as turbidity, suspended solids, and conductivity possibly due to the flushing out of nutrients during the rainy period. Other water parameters were mixed in the difference between wet and dry seasons, although the pattern of increased measurements from the upper region to the lower region is consistent across almost all of the water quality parameters.

Table 4.7. Wet Season Sector Analysis

Wet Season Land Use	**Wet**	**Arsenic (μg/L)**	**Copper (μg/L)**	**CL (mg/L)**	**Conductivity (uS/cm)**	**Turbidity (NTU)**	**Suspended Solids (mg/L)**	**Nitrites (mg/L)**	**Reactive Phosphorus (mg/L)**	**pH**	**Nitrates (mg/L)**	**TDS (g/L)**	**DO (mg/L)**	**Salinity (ppt)**
Upper Agriculture	Mean	0.09	0.65	6.83	96.28	31.13	19.67	0.35	5.10	8.00	104.92	0.06	4.41	0.04
	StDev	0.12	1.09	1.60	17.92	29.96	14.36	0.56	7.97	0.39	134.46	0.01	2.81	0.01
	CV	1.44	1.69	0.23	0.19	0.96	0.73	1.59	1.56	0.05	1.28	0.20	0.64	0.16
	Max	0.23	1.91	8.40	109.13	65.70	36.00	1.00	14.30	8.41	200.00	0.06	7.06	0.04
	Min	0.01	0.01	5.20	75.80	12.60	9.00	0.01	0.40	7.63	9.84	0.05	1.46	0.03
Middle Agriculture	Mean	0.49	4.00	77.02	370.63	68.36	45.64	1.42	3.47	7.24	163.38	0.22	42.10	0.35
	StDev	0.36	4.74	120.13	527.11	50.46	31.15	1.32	4.33	0.70	81.88	0.32	88.27	0.43
	CV	0.74	1.19	1.56	1.42	0.74	0.68	0.93	1.25	0.10	0.50	1.42	2.10	1.22
	Max	1.01	11.61	286.40	1308.33	133.00	81.00	3.00	11.05	8.38	200.00	0.79	200.00	1.00
	Min	0.01	0.01	2.70	67.70	1.90	5.18	0.01	0.70	6.50	16.90	0.04	1.70	0.03
Adjacent to Wetland	Mean	1.97	2.81	355.23	1694.32	42.89	32.25	1.38	2.13	7.35	156.81	1.47	3.89	1.77
	StDev	2.90	5.12	530.05	2822.09	42.68	30.98	1.05	1.32	0.85	80.12	3.31	3.34	3.06
	CV	4.46	2.68	19.24	19.21	0.54	0.58	0.53	1.66	0.12	0.40	41.34	1.29	54.00
	Max	8.42	14.94	1372.37	8460.57	100.00	82.00	3.00	5.00	9.38	200.00	9.60	11.94	8.56
	Min	0.03	0.01	7.50	99.00	0.32	0.00	0.00	0.80	6.60	17.90	0.06	2.28	0.04

Table 4.8. Dry Sector Analysis

Dry Season Land Use	Dry	Arsenic (µg/L)	Copper (µg/L)	CL (mg/L)	Conductivity (uS/cm)	Turbidity (NTU)	Suspended Solids (mg/L)	Nitrites (mg/L)	Reactive Phosphorus (mg/L)	pH	Nitrates (mg/L)	TDS (g/L)	DO (mg/L)	Salinity (ppt)
Upper Agriculture	Mean	10.15	1.32	22.18	308.34	6.82	10.40	0.60	2.62	8.19	81.62	0.16	5.31	0.12
	StDev	20.95	0.71	17.37	292.99	5.30	12.93	0.55	2.45	0.80	108.09	0.13	2.34	0.13
	CV	2.06	0.54	0.78	0.95	0.78	1.24	0.91	0.93	0.10	1.32	0.84	0.44	1.01
	Max	47.61	1.99	49.80	813.00	12.80	32.00	1.00	6.80	8.86	200.00	0.38	8.19	0.34
	Min	0.15	0.27	4.50	131.50	0.25	0.00	0.00	0.40	7.07	0.80	0.07	3.01	0.05
Middle Agriculture	Mean	2.63	1.79	27.18	263.28	25.16	18.75	4.19	3.19	7.39	76.08	0.16	3.65	0.10
	StDev	2.24	1.33	12.23	83.37	17.51	7.27	10.64	1.76	0.31	102.62	0.05	1.31	0.03
	CV	0.85	0.74	0.45	0.32	0.70	0.39	2.54	0.55	0.04	1.35	0.32	0.36	0.29
	Max	6.92	4.42	46.80	399.50	65.10	26.00	30.50	4.90	7.75	200.00	0.24	5.56	0.17
	Min	0.38	0.26	15.50	192.70	7.15	4.00	0.00	0.00	6.76	1.10	0.12	1.75	0.08
Adjacent to Wetland	Mean	3.81	291.13	275.51	1031.70	14.74	13.86	4.33	3.16	7.30	143.02	2.66	2.84	2.31
	StDev	4.68	765.01	353.09	988.29	9.63	7.86	9.65	1.24	0.39	89.91	5.12	1.93	4.74
	CV	1.23	2.63	1.28	0.96	0.65	0.57	2.23	0.39	0.05	0.63	1.93	0.68	2.05
	Max	14.20	2026.00	1000.00	2477.00	28.30	25.00	24.00	4.50	7.86	200.00	13.05	6.16	11.94
	Min	0.73	1.63	17.60	228.80	0.59	2.00	0.00	0.80	6.95	2.10	0.13	1.20	0.10

Synthesizing Data: NDVI and Water Quality Parameters

Riparian buffers and wetlands are known to improve water quality by reducing the concentration and load of pesticides, excess nutrients and sediments entering streams (Carpenter et al 1998; Schulz and Peall 2001; Hill 1996; Vellidis et al 2002). Using the normalized vegetation difference index (NDVI) for the study area as a surrogate measurement for biomass and vegetative productivity, is there a relationship between NDVI and water quality parameter measurements of surface water for the study area? The assumption would be that high levels of vegetative productivity translated as riparian buffers would act to uptake excess nutrients and act as a filter for pesticides and sediment. NDVI values adjacent to water quality measurements could indicate a relationship on the levels of nonpoint source pollution detected.

Study Area

The study is comprised of the area adjacent to the Pacaya River as discussed earlier in this chapter.

Data sets and GIS Utilization

Data for water quality parameters are the same as discussed previously in this chapter. The mean NDVI measurements used are the same as previously calculated for the analysis in Chapter 3. There were two sets of water quality parameters that matched the dates of available satellite imagery and resulting NDVI values, February 2011 and December 2011. Given the quality of wet season satellite imagery, excessive cloud cover in most of the study area made it infeasible possible to match enough June 2011 water quality variables with NDVI data.

Water quality and NDVI values were manipulated using ESRI ArcGIS version 10 geographic information systems. Buffers around each water quality point were created with a radius of 90 and 120 meters. These buffers were used to “clip” the NDVI values for each water quality parameter measurement point. Data points in areas overlapping the plantations were excluded.

Statistical analysis

A non-parametric method rank correlation coefficient method, Sprearman’s rho, was used because the data did not satisfy the normal distribution assumption (Zar 1999). Spearman's rank correlation coefficients were calculated between the mean NDVI values and the water quality measures using IBM SPSS v.19. The null hypothesis is that there is not an association between the two variables; the alternate that there is an association. The values for the rank correlation coefficient range between -1 and +1, and describe the magnitude and direction of the relationship between the two variables. The strongest correlations are values close to -1 or +1. For values 0.9 to 1, the correlation is very strong, between 0.7 and 0.89 strong, 0.5-0.69 moderate, and greater than 0.5 significant.

Results and Discussion

Table 4.9 shows the Spearman's rank correlation values for both February 2011 and December 2011 values. Although a buffer value was calculated for 120 meters, the values were essentially the same so that the table includes only 90 meter buffer values. Results varied from February and December observations. The parameters that consistently showed a relationship were dissolved oxygen and pH, although the relationships were much greater for the February 2011 data. Dissolved oxygen can be increased by a decrease in excess nutrients and this positive value may indicate that plants are using the excess nutrients, increasing dissolved oxygen, increasing plant growth (Carpenter et al. 1998a, Griffith 2002). Levels of pH both had a significantly negative correlation to NDVI over the area of study; therefore areas with higher NDVI had values closer to neutral as opposed to basic pH values, possibly the result of soils and the application of nitrogen. Both chloride and arsenic showed strong positive significance for February, but showed no significance in December 2011. Nitrites show a somewhat significant negative relationship but only in December 2011. It can be expected that plants could uptake excess nutrients, the effect being that there is an inverse relationship between NDVI and nitrites. Given that the nitrate measurements were extremely high, above testing limits, across all measuring sites, this relationship is not possible to determine. Given the limited data points and finding good quality satellite images for corresponding water quality analysis, this investigation only can serve as a test to see if this type of inquiry is possible.

Utilizing NDVI and its correlation to water quality parameters suggests that remote sensing observations could be a way to signal changes that could affect water quality given the expense and difficulty of obtaining field measurements in this area. Given the history of wetland removal and the location of plantations in close proximity to streams (in some cases right against the stream), increasing or creating riparian buffers could aid in water quality improvements. In addition, restoring wetlands and refraining from converting more wetlands to agriculture could also have a positive impact on water quality.

Table 4.9. Spearman's Rho NDVI and Water Quality for February 2011 and December 2011, significant values.

Feb-11				Dec-11		
Water Quality Parameter	Correlation Coefficient (rho value)	Significance (p value)		Water Quality Parameter	Correlation Coefficient (rho value)	Significance (p value)
Arsenic	0.867	0.002		Nitrites	-0.502	0.168
Chloride	0.7	0.036		Dissolved Oxygen	-0.483	0.187
Dissolved Oxygen	-0.786	0.021		pH	-0.467	0.205
pH	-0.633	0.067				

Conclusions

Although Guatemala has significant geologic and meteorological hazards, the northern part and also the coastal part of the southern section of the country, especially, have agricultural value and further potential. Within the latter region, the area on the north adjacent to the Pacific Ocean and Mexico is the setting for the study area. It contains soils that are potentially rich because the source is detritus from the volcanic ranges to the northeast and precipitation is adequate, although not equally distributed into wet and dry seasons. Currently, however, the country's physical assets are offset to a considerable extent by its low HDI ranking.

In the past twenty years, acceleration of land-use changes in this Pacific coastal plain of southwest Guatemala, from native arable and pasture lands to oil palm and banana plantations, has raised serious concerns about the effects of these changes on the human population and the overall ecosystem. Remote-sensing analyses, together with field observations and water analyses have documented and characterized changes that are thought in the long-term to be unsustainable. These changes include: loss of productivity as measured by NDVI, measureable contamination of streams by sediment and chemicals, and associated deterioration of lands adjoining plantations.

A significant finding of this research is that the consistent high-level of productivity for the banana and palm plantations is in sharp contrast to the declining productivity of non-plantation sites. Analysis of the remote-sensing data at the study sites showed that the introduction and expansion of plantations adversely affected the adjacent lands, with an increase in NDVI over time for the plantations and a varied, but generally downward trend for the non-plantation sites.

Water analyses that included determinations of key soluble constituents and properties confirmed the contamination of the streams and other water sources in the study area; especially troubling are the levels of nitrates and nitrites, which are harmful to humans. While it is known that the adjoining lands experience an excess of water during the wet season, when the plantations use drainage procedures, and a shortage of water during the dry season, when the plantations use much of the available water for irrigation, it was not possible establish the plantations as the direct source of the measured contaminants.

The results of the analyses performed in this research provide valuable information to the residents and government agencies that must decide on policies and practices in terms of sustainability. Further, this research shows that remote sensing can be used more extensively in assessing and evaluating land-use changes, a major factor in developing countries with very restricted funds for this purpose. Therefore, this research may serve as a model for those countries to consider in evaluating their agricultural resources in terms of sustainability as well as development.

This research also reinforces the notion that remote sensing and satellite images can provide unbiased, systematic and available data sources for environmental evaluation. This is extremely useful when analyzing areas such as Guatemala, where field data collection is fraught with access and political challenges. This study also reinforces the value of combining remote sensing data with water quality field data to bring an additional dimension to studies that is not present when using just one of those data components.

In addition, this study reveals potential future studies on the use of remote sensing data for: 1) cost/benefit analysis for plantation expansion in Guatemala or other areas with conflicts in resource allocation, 2) proof or disproof by banana or palm plantations for certifications such as Roundtable on Sustainable Requirements for Biofuels, 3) early warning to land-use sustainability issues, and 4) predicting water-quality parameters and undesirable patterns.

Appendix of Tables

A-I. Tables of NDVI Mean and Standard Deviation Values

Table A3.1. Dry Season NDVI Mean Values

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
1997	0.31	0.14	0.54	0.11	0.40	0.33	0.20
1999	0.52	0.51	0.33	0.30	0.45	0.17	0.59
2000	0.60	0.59	0.57	0.51	0.49	0.67	0.64
2008	0.46	0.37	0.22	0.14	0.34	0.54	0.65
2010	0.51	0.47	0.40	0.36	0.38	0.57	0.70

Table A3.2. Dry Season NDVI Standard Deviation

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
1997	0.12	0.15	0.13	0.15	0.13	0.14	0.16
1999	0.10	0.12	0.16	0.21	0.12	0.19	0.06
2000	0.10	0.11	0.11	0.13	0.14	0.07	0.05
2008	0.10	0.14	0.10	0.09	0.13	0.04	0.02
2010	0.12	0.17	0.16	0.12	0.13	0.04	0.03

Table A3.3. Wet Season NDVI Mean Values

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
1997	0.31	0.14	0.54	0.11	0.40	0.33	0.20
1999	0.52	0.51	0.33	0.30	0.45	0.17	0.59
2000	0.60	0.59	0.57	0.51	0.49	0.67	0.64
2008	0.46	0.37	0.22	0.14	0.34	0.54	0.65
2010	0.51	0.47	0.40	0.36	0.38	0.57	0.70

Table A3.4. Wet Season NDVI Standard Deviation

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
1997	0.12	0.15	0.13	0.15	0.13	0.14	0.16
1999	0.10	0.12	0.16	0.21	0.12	0.19	0.06
2000	0.10	0.11	0.11	0.13	0.14	0.07	0.05
2008	0.10	0.14	0.10	0.09	0.13	0.04	0.02
2010	0.12	0.17	0.16	0.12	0.13	0.04	0.03

A-II. Tables of Frequency Distribution Permutation Values

Table A3.5. Frequency Distribution Wet Season Permutation Values 1997 – 2010

Valid Range	*Frequency*	*Percent*	*Cumulative Percent*
-0.14 through -0.10	3	14%	14%
-0.09 through -0.05	2	10%	24%
-0.04 through 0.00	6	29%	52%
0.01 through 0.05	5	24%	76%
0.06 through 0.10	3	14%	90%
0.11 through 0.15	2	10%	100%

Table A3.6. Frequency Distribution Dry Season Permutation Values 1998 - 2011

Valid Range	*Frequency*	*Percent*	*Cumulative Percent*
-0.15 through -0.10	5	24%	24%
-0.09 through -0.04	1	5%	29%
-0.03 through 0.02	7	33%	62%
0.03 through 0.08	4	19%	81%
0.09 through 0.14	2	10%	90%
0.14 through 0.19	2	10%	100%

Table A3.7. Frequency Distribution Wet Season Permutation Values 1997

Valid Range	*Frequency*	*Percent*	*Cumulative Percent*
-0.26 through -0.18	2	10%	10%
-0.17 through -0.09	5	24%	33%
-0.08 through 0.00	4	19%	52%
0.01 through 0.09	5	24%	76%
0.10 through 0.18	2	10%	86%
0.19 through 0.27	3	14%	100%

Table A3.8. Frequency Distribution Wet Season Permutation Values 2010

Valid Range	*Frequency*	*Percent*	*Cumulative Percent*
-0.17 through -0.11	3	14%	14%
-0.04 through -0.10	6	29%	43%
0.03 through -0.03	4	19%	62%
0.04 through 0.10	5	24%	86%
0.11 through 0.17	2	10%	95%
0.18 through 0.24	1	5%	100%

Table A3.9. Frequency Distribution Dry Season Permutation Values 1998

Valid Range	*Frequency*	*Percent*	*Cumulative Percent*
-0.14 through -0.09	3	14%	14%
-0.08 through -0.03	6	29%	43%
-0.02 through 0.03	4	19%	62%
0.04 through 0.09	5	24%	86%
0.10 through 0.15	2	10%	95%
0.16 through 0.21	1	5%	100%

Table A3.10. Frequency Distribution Dry Season Permutation Values 2011

Valid Range	*Frequency*	*Percent*	*Cumulative Percent*
-0.25 through -0.15	7	33%	33%
-0.14 through -0.04	3	14%	48%
-0.03 through 0.07	3	14%	62%
0.08 through 0.18	5	24%	86%
0.19 through 0.29	2	10%	95%
0.30 through 0.40	1	5%	100%

A-III. Tables of NDVI Trend Values Standard Deviation

Table A3.11. Wet Season NDVI Trend Values Standard Deviation

X	Y - Site 1	Y - Site 2	Y - Site 3	Y - Site 4	Y - Site 5	Y - Site 6	Y - Site 7
1997	0.10	0.13	0.13	0.15	0.13	0.10	0.07
1999	0.10	0.14	0.13	0.14	0.13	0.08	0.06
2000	0.10	0.14	0.13	0.13	0.13	0.07	0.05
2008	0.10	0.16	0.13	0.09	0.13	0.00	-0.01
2010	0.10	0.16	0.12	0.08	0.13	-0.01	-0.02

Table A3.12. Dry Season NDVI Trend Values Standard Deviation

X	Y - Site 1	Y - Site 2	Y - Site 3	Y - Site 4	Y - Site 5	Y - Site 6	Y - Site 7
1998	0.09	0.13	0.12	0.13	0.10	0.07	0.06
1999	0.09	0.14	0.12	0.13	0.10	0.07	0.06
2001	0.09	0.14	0.12	0.12	0.11	0.07	0.05
2009	0.10	0.15	0.13	0.08	0.14	0.06	0.01
2011	0.10	0.16	0.13	0.07	0.14	0.06	0.01

A-IV. Wet and Dry Season Data

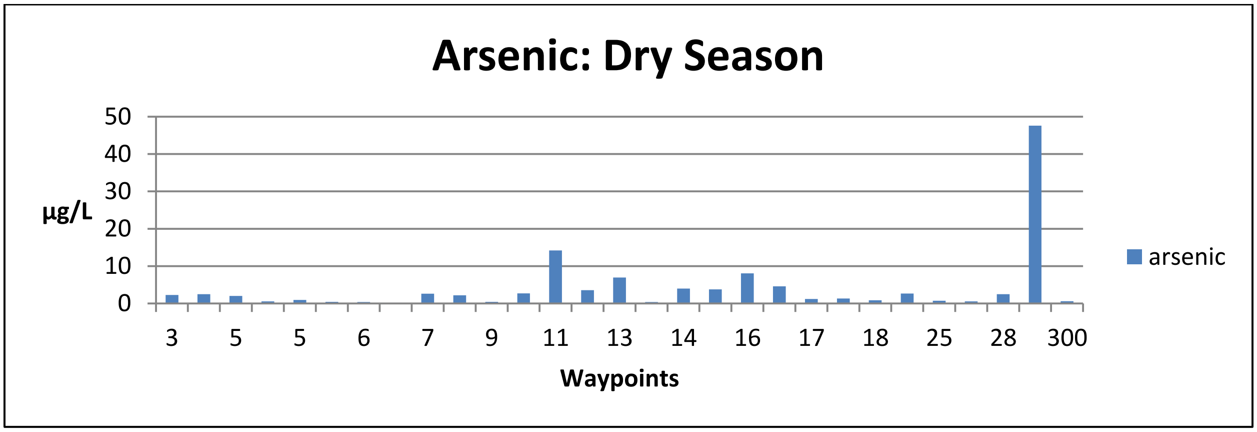
Table A4.1. Wet Season Water Quality Measurement Data

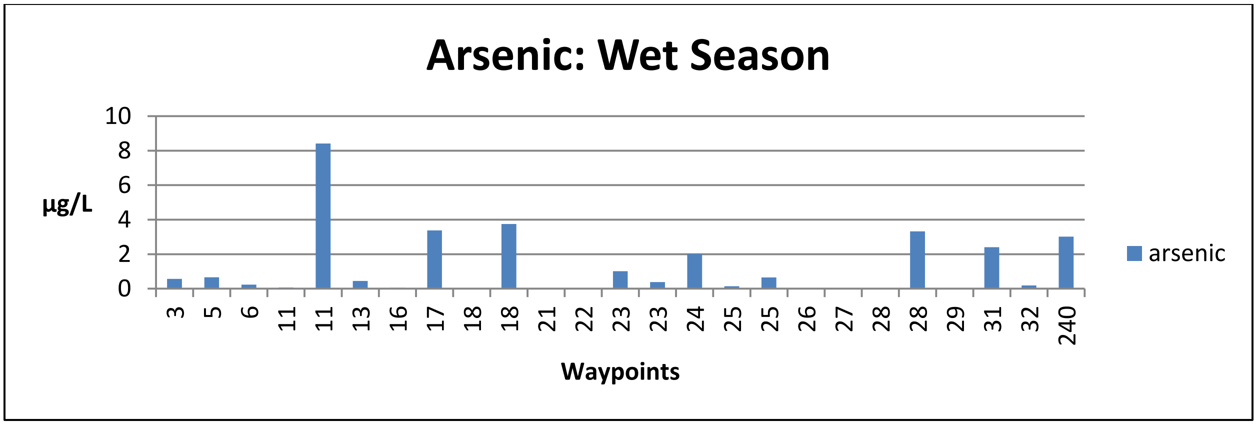
month	Waypoint	lat	long	arsenic	Copper	Selenium	Lead	Chromium	Cadmium	Chloride	Conductiv	Turbidity	SS	Phosphor	pH	Nitrates	Nitrites	Sum_of_t	Sum_of_t	TDS	ORP_1	DO	Salinity
Jul-12	3	14.58605	-92.0845	0.57	11.61		1.9	5.18	0.07	11.05	131.27	238	195	0.7	7.26	200	1	4.333333	9	0.08	280.05	3.30	0.06
Jul-12	5	14.53272	-92.1048	0.66	4.37		0.71	3.01	0.01	13.55	116.40	70.8	52	1	6.90	200	2	4.666667	14	0.07	226.90	2.37	0.05
Jul-12	6	14.56598	-91.979	0.23	1.91		0.13	1.56	0.05	6.90	109.13	15.1	9	0.6	8.41	200	1	4.333333	9	0.06	222.85	4.71	0.04
Jun-11	11	14.5078	-92.1356	0.066087	0.23	0.028775	0	0	0	1000	1510	9.56	10	1.9	7.05	200	0	4	4	9.602667	55.6	0.54	8.56
Jul-12	11	14.5078	-92.1356	8.42	14.94		0.16	3.68	0.4	1372.37	1500.00	4.18	10	1.9	6.60	200	1	4.333333	9	4.85	202.15	2.48	4.06
Jul-12	13	14.58673	-92.0403	0.45	4.42		0.59	2.39	0	71.00	222.27	133	72	2.9	7.19	200	3	5	19	0.13	312.40	1.70	0.09
Jun-11	16	14.56308	-92.0575	0.051417	0.01	0.022409	0	0.005919	0	14	349.7	1.67	0	0.9	7.24	200	0.006	4.002	4.03	0.211467	69.5	3.68	0.15
Jul-12	17	14.55973	-92.0669	3.38	1.65		0.61	1.62	0.17	37.00	785.67	0.95	2	1.1	7.52	200	2	4.666667	14	0.45	232.75	2.71	0.33
Jun-11	18	14.51748	-92.105	0.03068	0.02	0.023127	0	0	0	147.1	1554.3	1.15	0	1.7	7.31	36.6	0.041	0.745667	0.937	0.91	219.6	4.51	0.69
Jul-12	18	14.51748	-92.105	3.75	0.99		0.24	1.28	0.16	264.65	1510.83	0.32	0	1.8	7.12	200	2	4.666667	14	0.90	232.67	2.28	0.69
Jun-11	21	14.62343	-91.9952	0.017146	0.02	0.023578	0	0	0	14	86.5	180	147	0.7	7.11	200	0.014	4.004667	4.07	0.0531	198.3	6.08	0.04
Jun-11	22	14.61617	-91.9891	0.01483	0.03	0.023112	0	0	0	6.5	74.6	98	80	0.9	7.38	15.9	1	0.651333	5.318	0.04535	237.6	5.73	0.03
Jun-11	23	14.58648	-92.0417	1.01483	0.02	0.022986	0	0	0	13.4	67.7	99	81	1.9	8.38	16.9	2	1.004667	10.338	0.0431	149	3.42	0.03
Jul-12	23	14.58648	-92.0417	0.38	3.94		0.22	1.5	0.08	286.40	1308.33	64.8	41	0.8	6.50	200	2	4.666667	14	0.79	397.73	2.88	0.60
Jun-11	24	14.53197	-92.1046	2.01483	0.01	0.022941	0	0	0	7.5	125.6	100	82	2.9	9.38	17.9	3	1.358	15.358	0.075867	223.6	2.32	0.05
Jun-11	25	14.5115	-92.1319	0.14283	0.02	0.022995	0	0	0	9.1	99	77.9	51	5	7.3	200	1	4.333333	9	0.06164	204.9	2.61	0.04
Jul-12	25	14.5115	-92.1319	0.65	1.91		0.12	1.5	0.06	27.55	146.88	79.2	53	0.8	7.17	200	2	4.666667	14	0.08	199.00	2.59	0.06
Jun-11	26	14.56282	-92.0181	0.017123	0.02	0.022758	0	0	0	8.4	103.9	65.7	36	14.3	7.63	200	0.049	4.016333	4.245	0.063033	144.7	1.46	0.04
Jun-11	27	14.58637	-92.0847	0.014085	0.01	0.023138	0	0	0	2.7	123.6	43.1	29	0.7	6.89	200	0.009	4.003	4.045	0.0761	140.3	2.52	0.05
Jun-11	28	14.54762	-92.0821	0.029187	0.02	0.022181	0	0	0	24	451.9	16	20	6.7	7.31	36.5	0.022	0.737333	0.84	0.2754	183.1	2.84	0.2
Jul-12	28	14.54762	-92.0821	3.32	5.75		0.66	1.51	0.62	16.20	479.08	52.9	32	1.5	7.41	200	2	4.666667	14	0.27	239.40	3.40	0.20
Jun-11	29	14.56383	-91.9805	0.011579	0.01	0.022632	0	0	0	5.2	75.8	12.6	14	0.4	7.96	9.84	0.009	0.1998	0.2418	0.0475	106.9	7.06	0.03
Jul-12	31	14.56303	-92.0165	2.4	1.35		0.15	1.44	0.16	34.35	552.75	10.3	15	1.3	7.23	200	3	5	19	0.30	266.65	2.38	0.22
Jul-12	32	14.54828	-91.9861	0.19	2.61		0.3	1.85	0	5.68	110.25	35.1	21	0.6	7.82	200	2	4.666667	14	0.06	228.85	3.96	0.04
Jun-11	240	14.61617	-92.0009	3.01483	0.03	0.022924	0	0	0	5.5	84.7	101	83	3.9	10.38	18.9	4	1.711333	20.378	0.0531	210	3.41	0.04

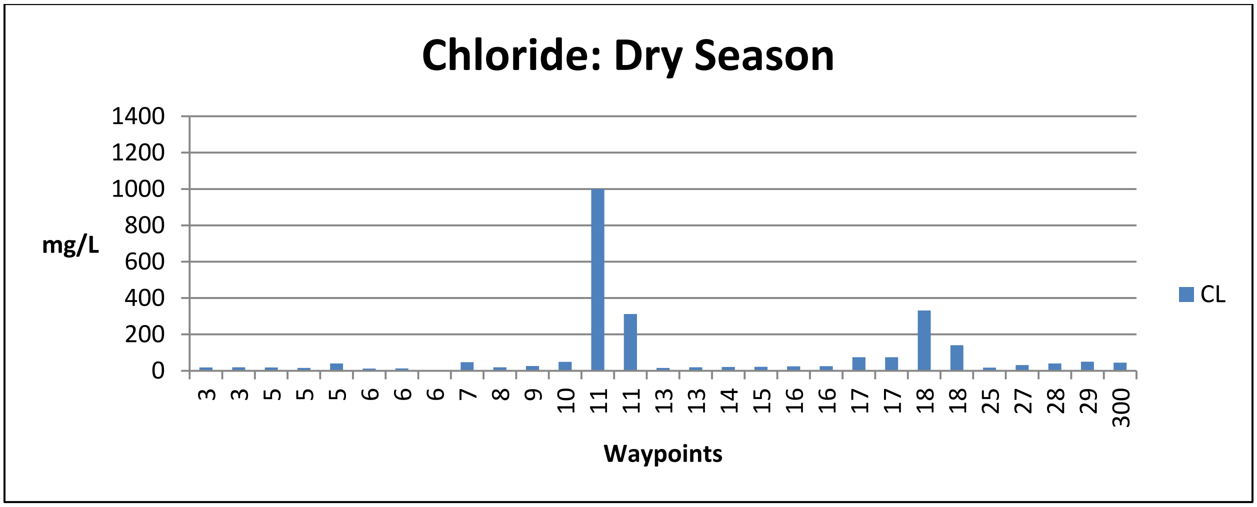
Table A4.2. Dry Season Water Quality Measurement Data

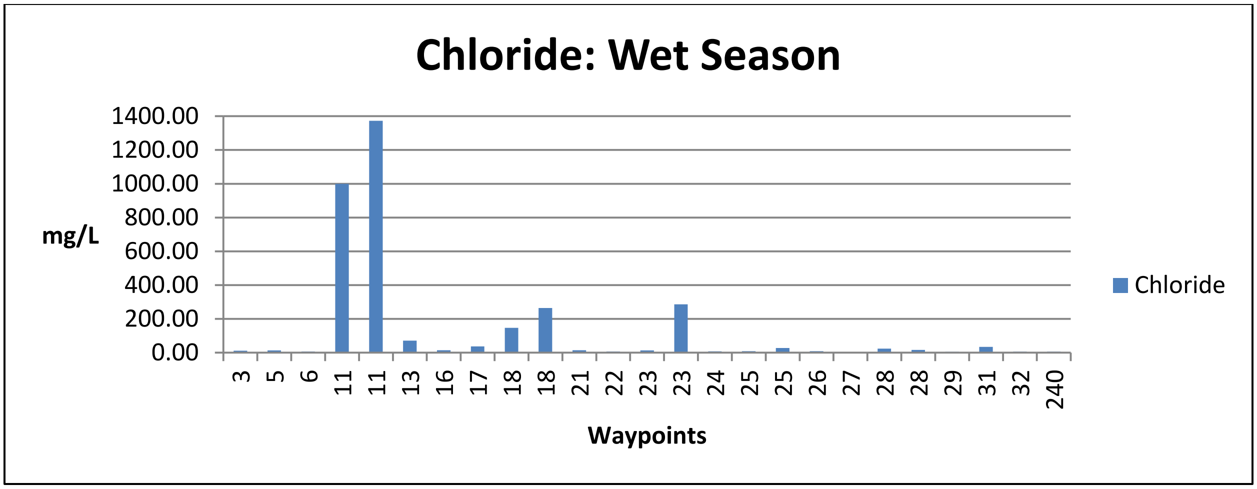
month	Waypoint	lat	long	arsenic	CL	conductiv	Turbidity	Sus_solid	Nitrites	Phosphate	pH	NO3	TDS	CL	ORP_1	DO	Salinity
d	5	14.53272	-92.1048	0.94	40.1	453.5	20.1	16	24	3.5	6.95		0.2704	40.1	173.4	1.57	0.2
d	6	14.56598	-91.979	0.15	4.5	319	12.8	8	0	2.4	8.69		0.1807	4.5	158.6	4.44	0.13
d	11	14.5078	-92.1356	3.53	312.1		11.3	11	0	2.8	7.19		1.5275	312.1	162.1	1.59	1.2
d	13	14.58673	-92.0403	0.38	19.3	192.7	30.5	24	30.5	4.4	7.37		0.117	19.3	105.9	3.11	0.08
d	16	14.56308	-92.0575	3.98	25.4	439.3	8.5	3	0	0.9	7.27		0.312	25.4	163.7	4.71	0.2
d	17	14.55973	-92.0669	1.20	74.2		2.38	1	0	1.3	7.37		1.261	74.2	152.1	3.55	0.92
d	18	14.51748	-92.105	0.86	140.4	728	0.59	2	0	0.8	7.12		0.832	140.4	138.8	3.24	0.32
d	25	14.5115	-92.1319	0.73	17.6	230.9	16	12	0	2.6	6.97		0.1359	17.6	166.7	1.25	0.1
d	27	14.58637	-92.0847	0.53	31	399.5	16.5	17	0	0	6.76		0.2379	31	150.1	1.75	0.17
d	28	14.54762	-92.0821	2.49	40.4	844	37.5	50	0	14.5	7.23		0.429	40.4	178.4	3.92	0.37
d	29	14.56383	-91.9805	47.61	49.8	813	0.25	0	1	0.4	7.61		0.3835	49.8	130.1	3.51	0.34
d	300	14.58702	-92.0707	0.60	44.4	390.1	20.8	18	0	3.4	7.22		0.2314	44.4	115.9	2.03	0.25
month	Waypoint	lat	long	arsenic	CL	conductiv	Turbidity	Sus_solid	Nitrites	Phosphate	pH	NO3	TDS	CL	ORP_1	DO	Salinity
f	3	14.58605	-92.0845	2.27	18.6	206.2	15.6	15	0	2.4	7.22	1.1	0.1261	18.6		3.47	0.09
f	3	14.58605	-92.0845	2.48	19.4	202.5	17.4	13	1	4.2	7.43	1.4	0.1244	19.4	130.5	2.66	0.09
f	5	14.53272	-92.1048	1.99	18.4	228.8	21.4	22		4	7.73	2.1	0.1333	18.4		6.16	0.1
f	5	14.53272	-92.1048	0.55	15.8	213.7	23.4	20	2	4.8	7.7	1	0.1291	15.8	164.3	5.81	0.09
f	6	14.56598	-91.979	0.41	11.7	137	8.74	11	1	1.8	8.86	0.9	0.0785	11.7		8.19	0.05
f	6	14.56598	-91.979	0.35	12.7	127.1	6.1	11	0	2.3	8.23	0.9	0.0791	12.7	183.1	6.88	0.06
f	7	14.58695	-92.0648	2.60	46.8	200.8	22.3	20	1	2	7.44	1.6	0.1222	46.8	227.7	3.91	0.09
f	8	14.58762	-92.0395	2.18	19.2	141.2		32	1	6.8	7.07	6.4	0.0732	19.2	256.7	3.01	0.05
f	9	14.58528	-91.9476	0.42	25.7	131.5	5.5	1	0	1.7	8.71	0.8	0.0778	25.7	202.4	7.38	0.05
f	10	14.56303	-92.0165	2.68	49.2	493.6	7.38	13	1	2.2	7.77	4.2	0.3092	49.2	213	5.37	0.23
f	10	14.56303	-92.0165	7.96	26.95	153.5	97.5	101	1	15.7	8.07		0.093	26.95		4	0.07
f	10	14.56303	-92.0165	8.42		120.7	12.4	9	0	1.4	8.03	2.7	0.0719		134.1	4.26	0.05
f*	11	14.5078	-92.1356	14.20			5.46	9	1	3.9	7.86	56	13.0455		112.5	3.68	11.94
f	12	14.51258	-92.1134	2.66			28.3	25	1	4.5				400			
f	13	14.58673	-92.0403	6.93	15.5	231.9	7.15	4	0	1.8	7.41	1.3	0.1362	15.5	192.5	2.85	0.1
f	14	14.58698	-92.0401	3.98	20.5	239.1	23.3	26	1	4.8	7.74	2.2	0.1366	20.5	199.6	5.56	0.1
f	15	14.58737	-92.0395	3.77	21.3	245.9	65.1	26	0	4.9	7.75	2.4	0.1407	21.3	161.1	5	0.1
f*	16	14.56308	-92.0575	8.05	23.9	377.2	2.27	0	1	1.5	7.4	0.9	0.2258	23.9	137	2.21	0.16
f	17	14.55973	-92.0669	1.20	74.3	858.3	0.21	0	0	1.4	7.49	3	0.494	74.3	157.3	3.36	0.37
f	18	14.51748	-92.105	0.86	332		0.22	0	1	1.4	7.57	6.2	0.8461	332	194.2	3.75	0.64

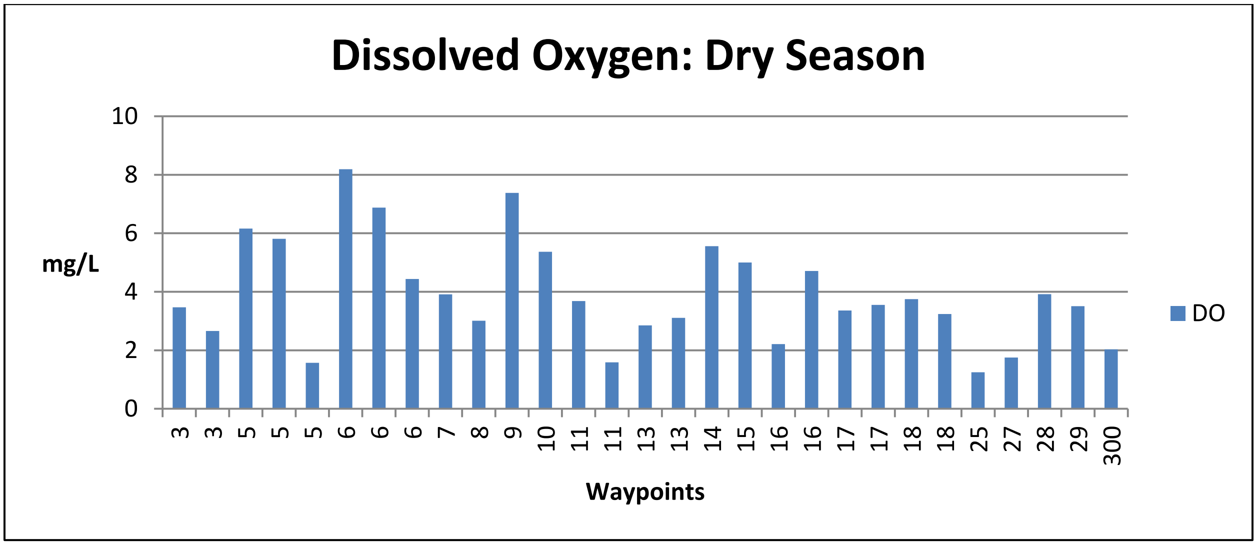
A-V. Water Quality Graphs for Wet and Dry Seasons Arranged by Waypoint Locations

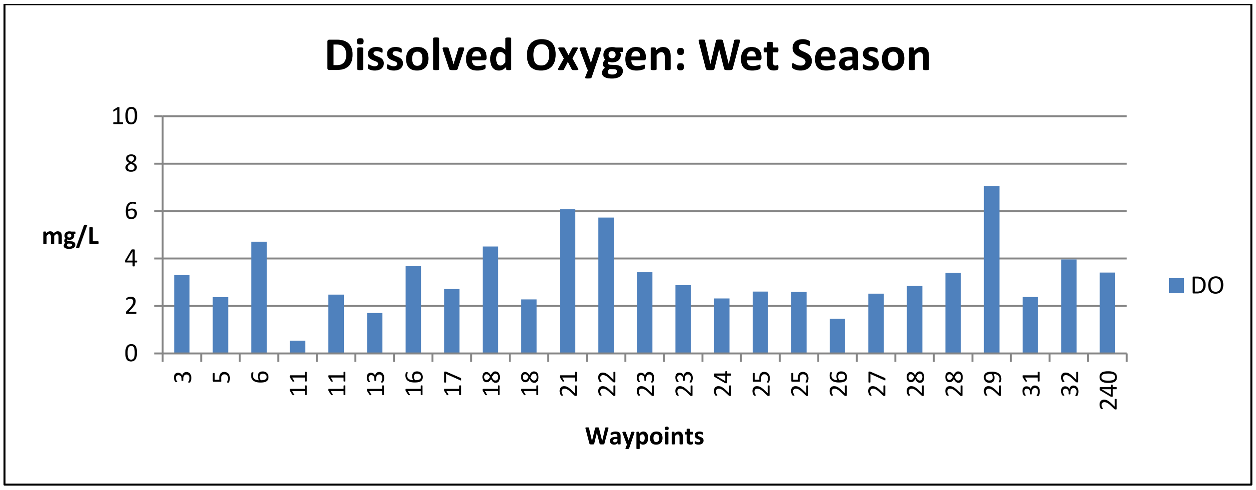


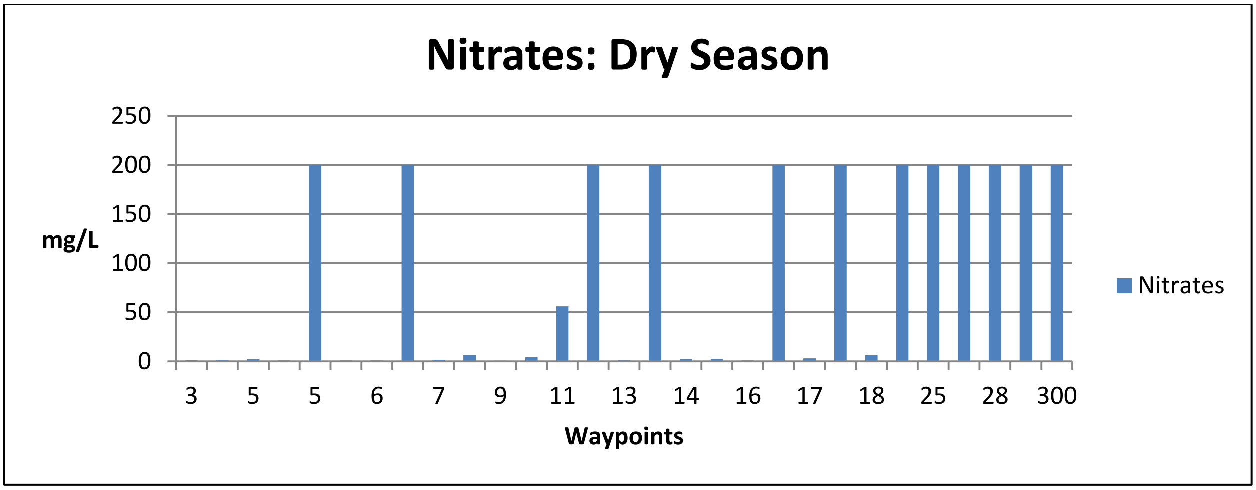


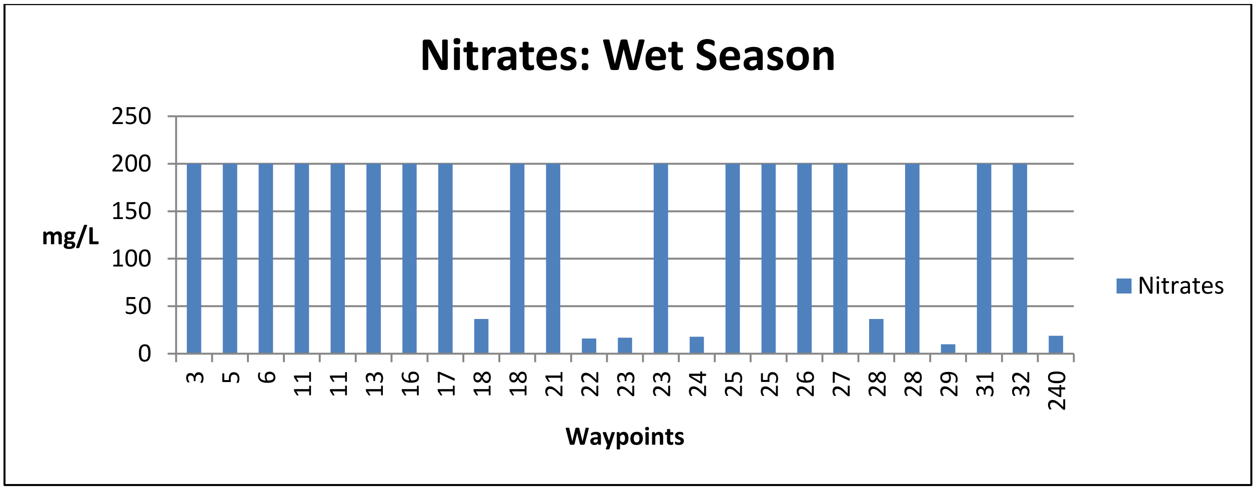


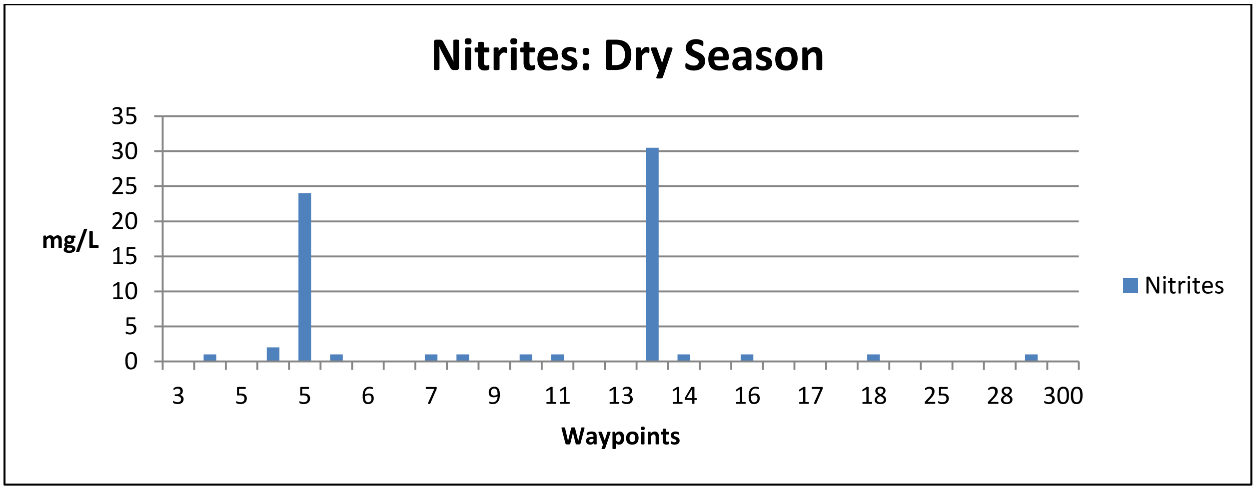

Chloride: Wet Season
mg/L
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Chloride

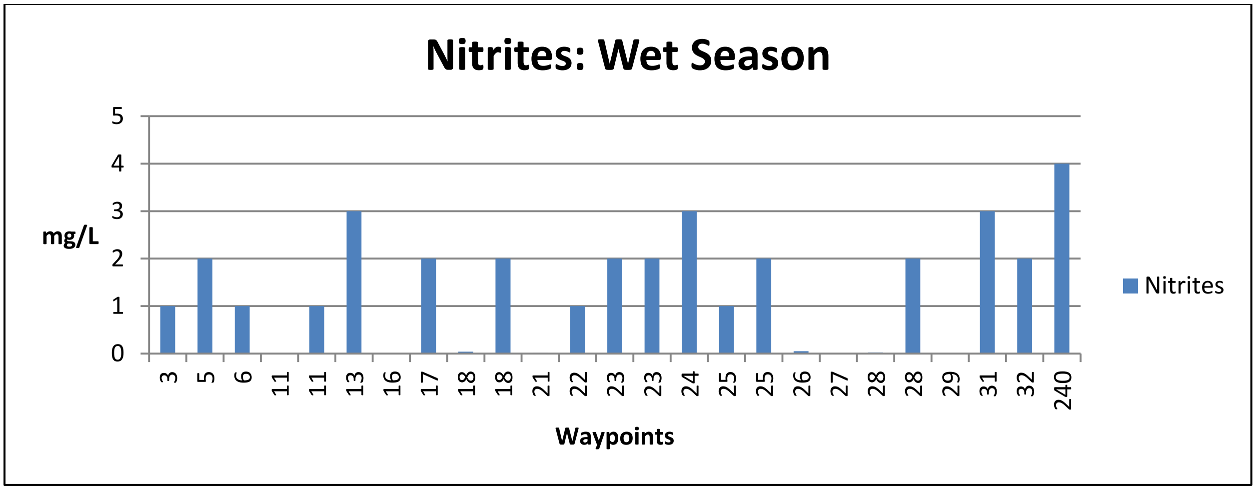

Dissolved Oxygen: Dry Season
mg/L
10
8
6
4
2
0
3
3
5
5
5
6
6
6
7
8
9
10
11
11
13
13
14
15
16
16
17
17
18
18
25
27
28
29
300
Waypoints
DO

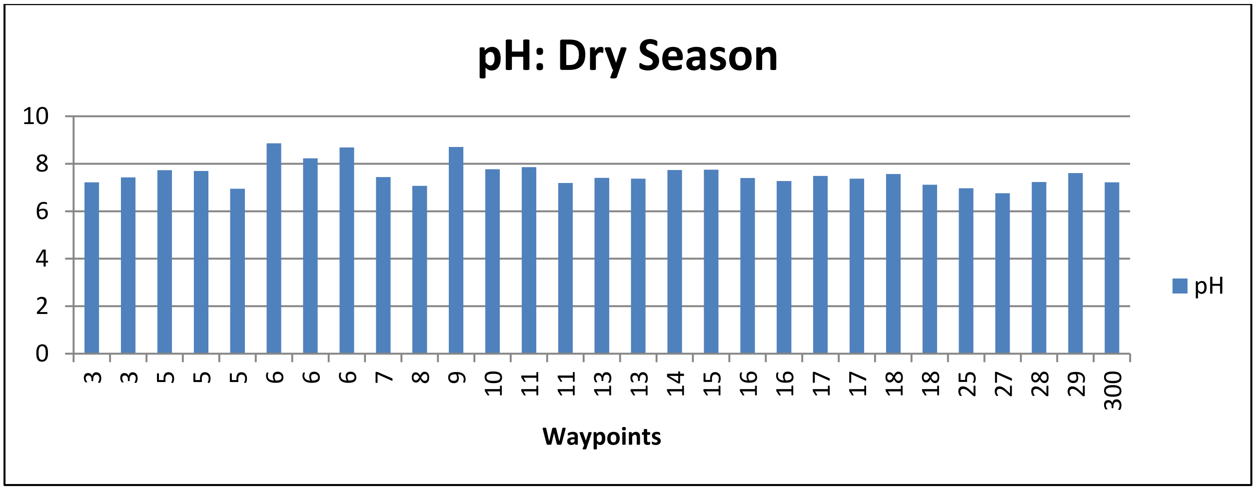

Dissolved Oxygen: Wet Season
mg/L
10
8
6
4
2
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
DO

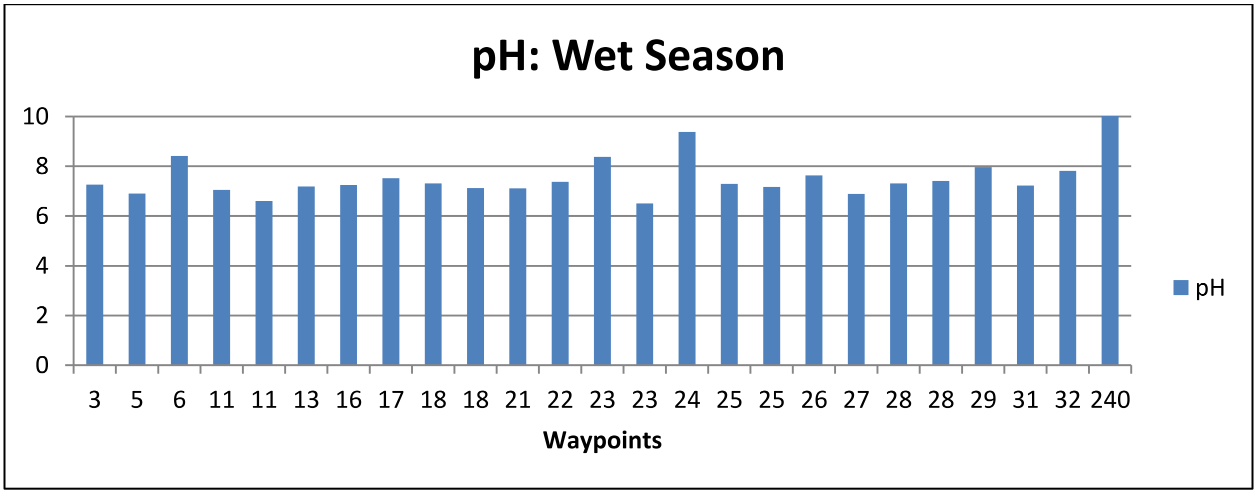

Nitrates: Dry Season
mg/L
250
200
150
100
50
0
3
5
5
6
7
9
11
13
14
16
17
18
25
28
300
Waypoints
Nitrates

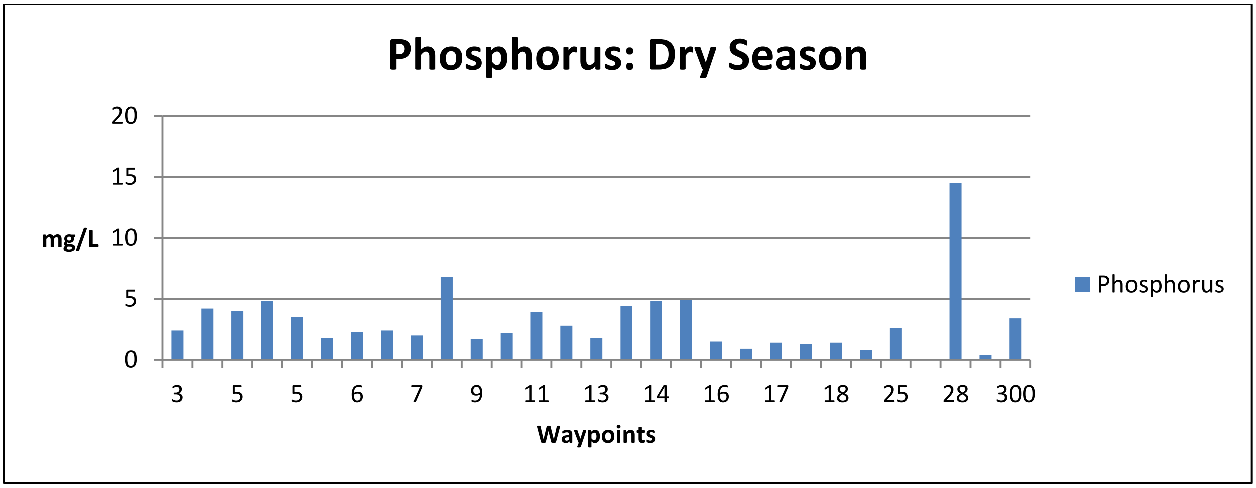

Nitrates: Wet Season
mg/L
250
200
150
100
50
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Nitrates

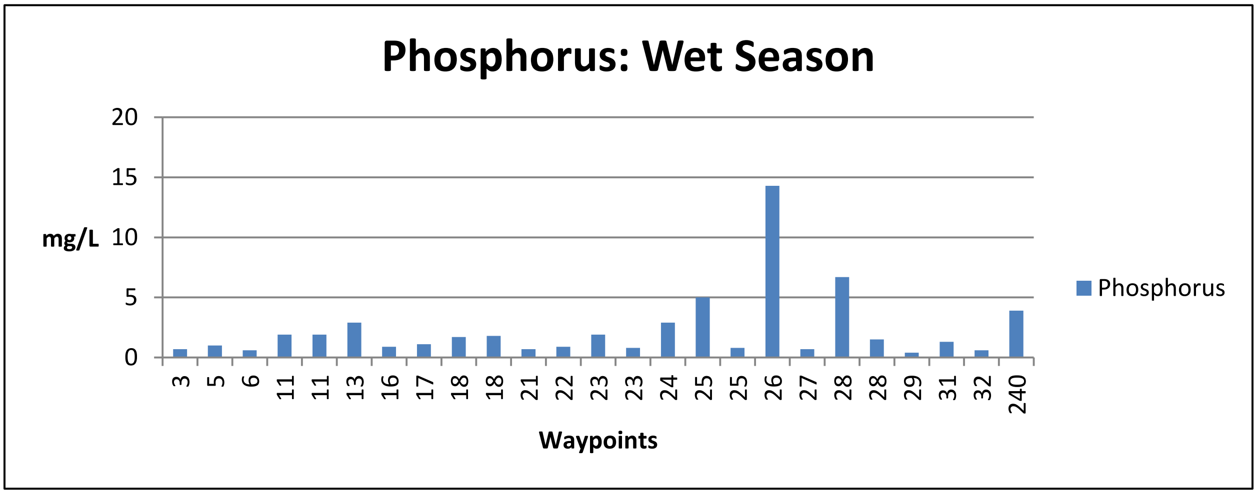

Nitrites: Dry Season
mg/L
35
30
25
20
15
10
5
0
3
5
5
6
7
9
11
13
14
16
17
18
25
28
300
Waypoints
Nitrites

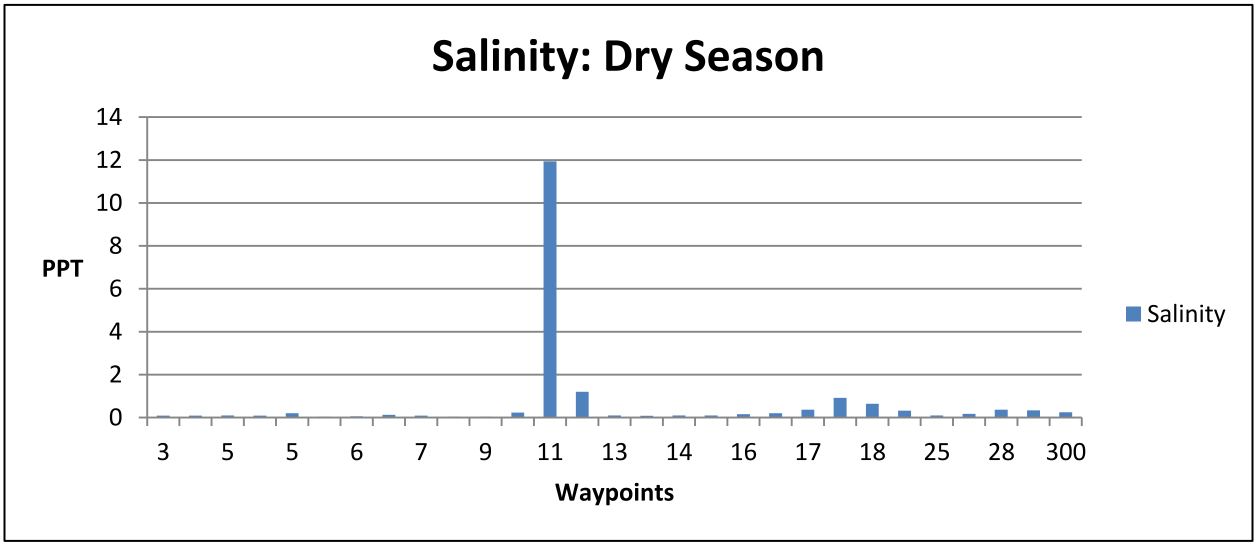

Nitrites: Wet Season
mg/L
5
4
3
2
1
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Nitrites

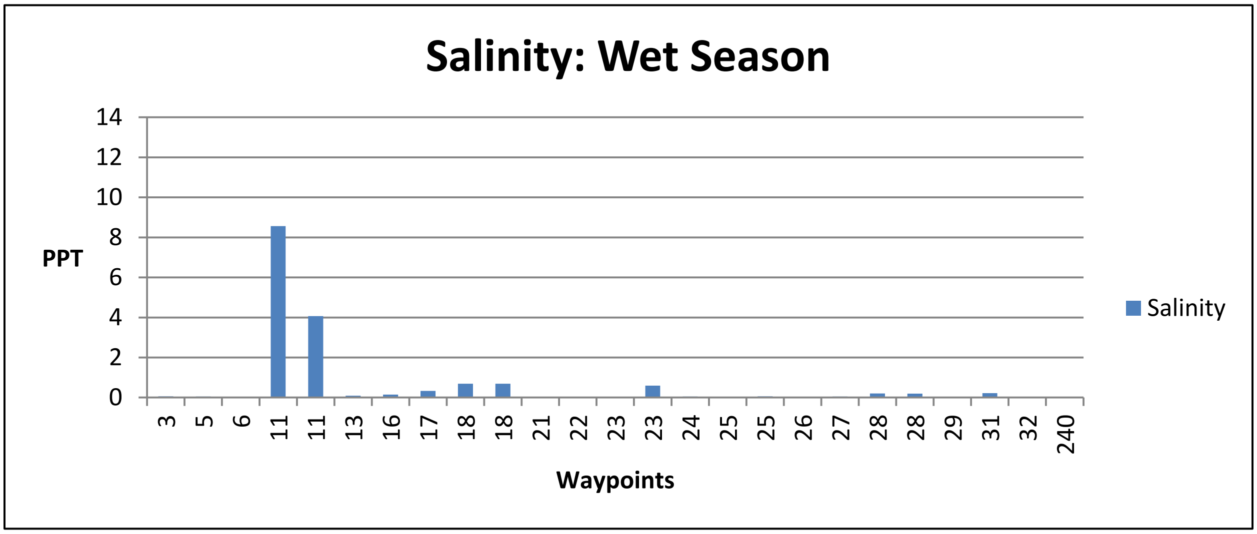

pH: Dry Season
10
8
6
4
2
0
3
3
5
5
5
6
6
6
7
8
9
10
11
11
13
13
14
15
16
16
17
17
18
18
25
27
28
29
300
Waypoints
pH

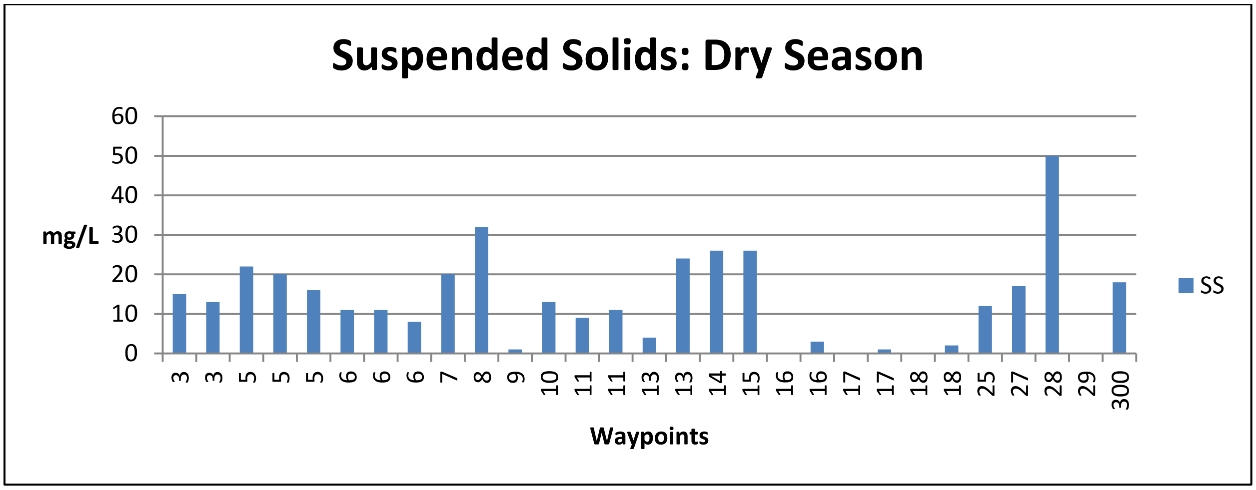

pH: Wet Season
10
8
6
4
2
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
pH

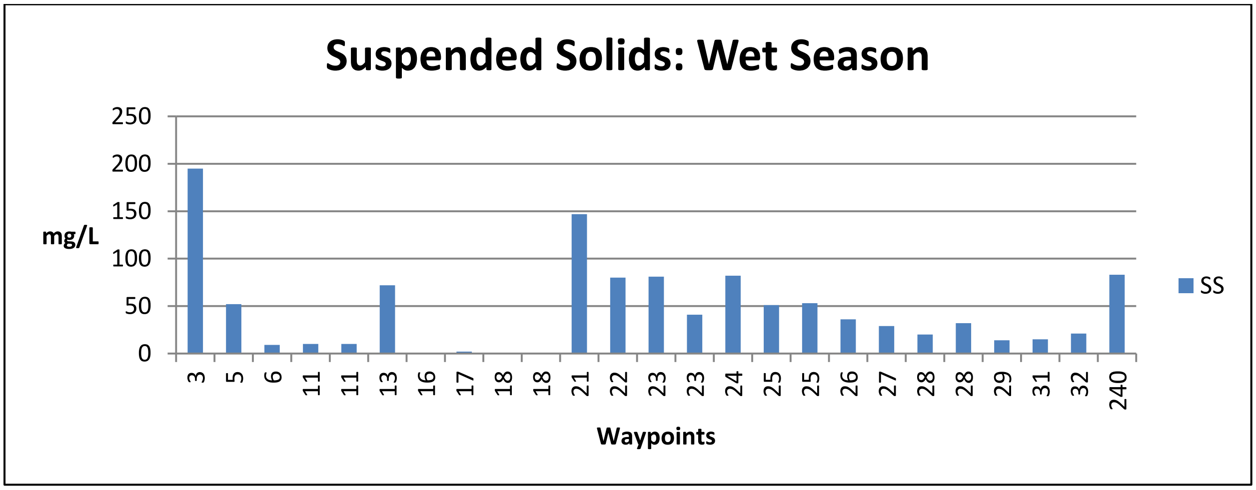

Phosphorus: Dry Season
mg/L
20
15
10
5
0
3
5
5
6
7
9
11
13
14
16
17
18
25
28
300
Waypoints
Phosphorus

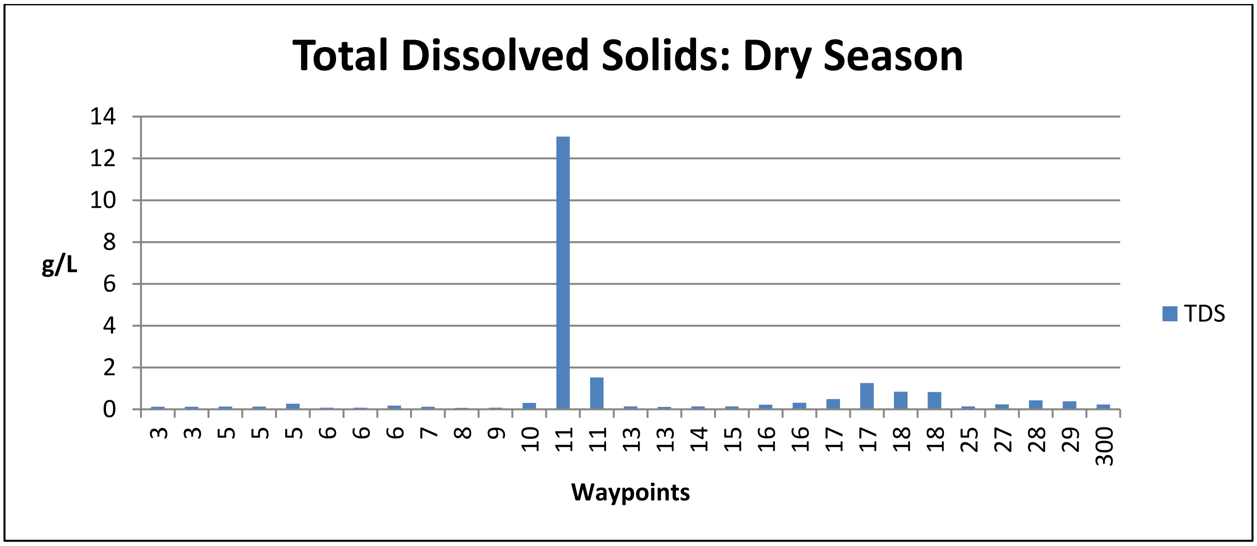

Phosphorus: Wet Season
mg/L
20
15
10
5
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Phosphorus

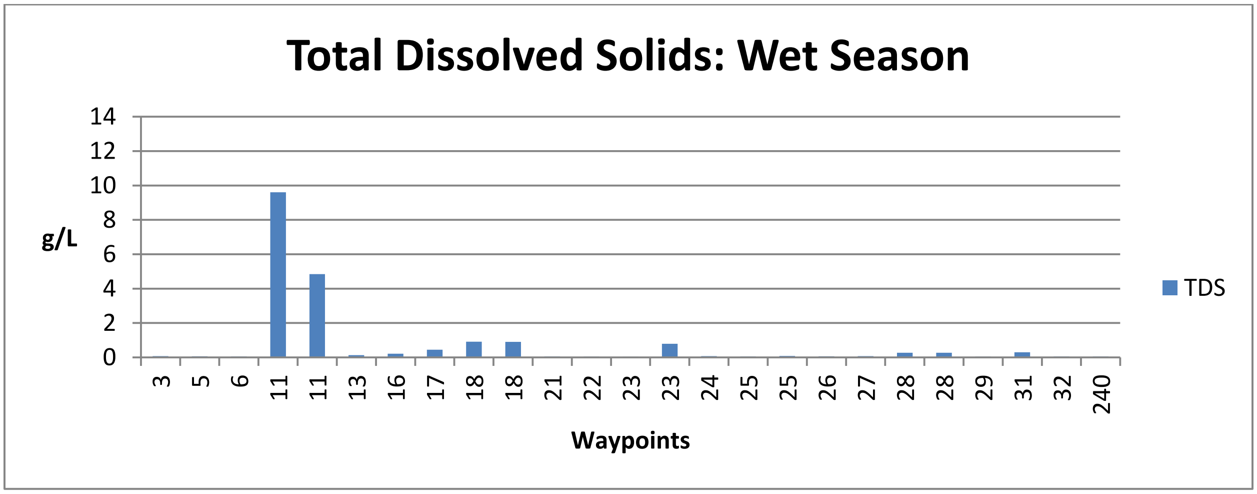

Salinity: Dry Season
PPT
14
12
10
8
6
4
2
0
3
5
5
6
7
9
11
13
14
16
17
18
25
28
300
Waypoints
Salinity

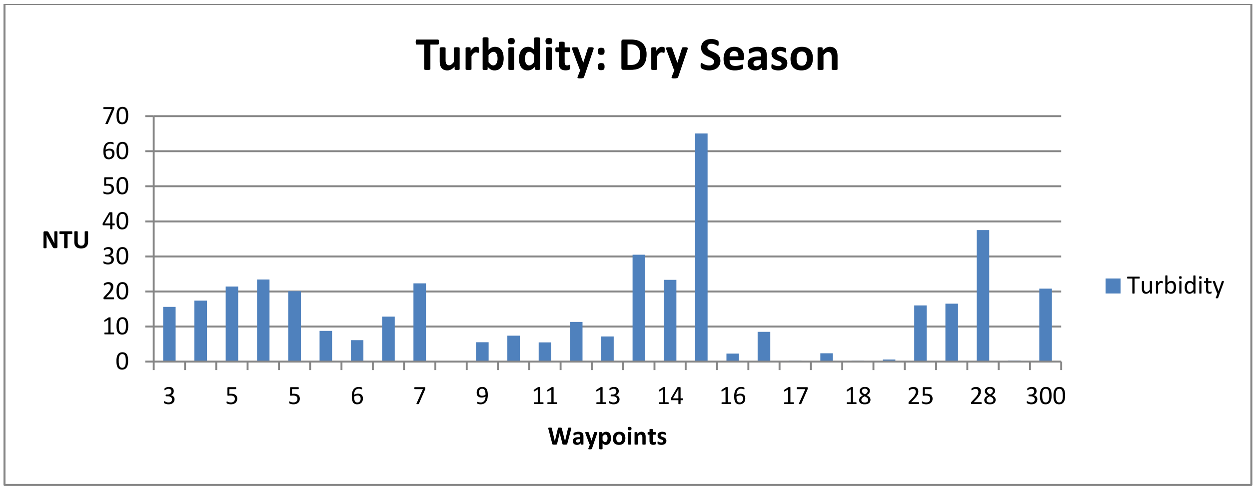

Salinity: Wet Season
PPT
14
12
10
8
6
4
2
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Salinity

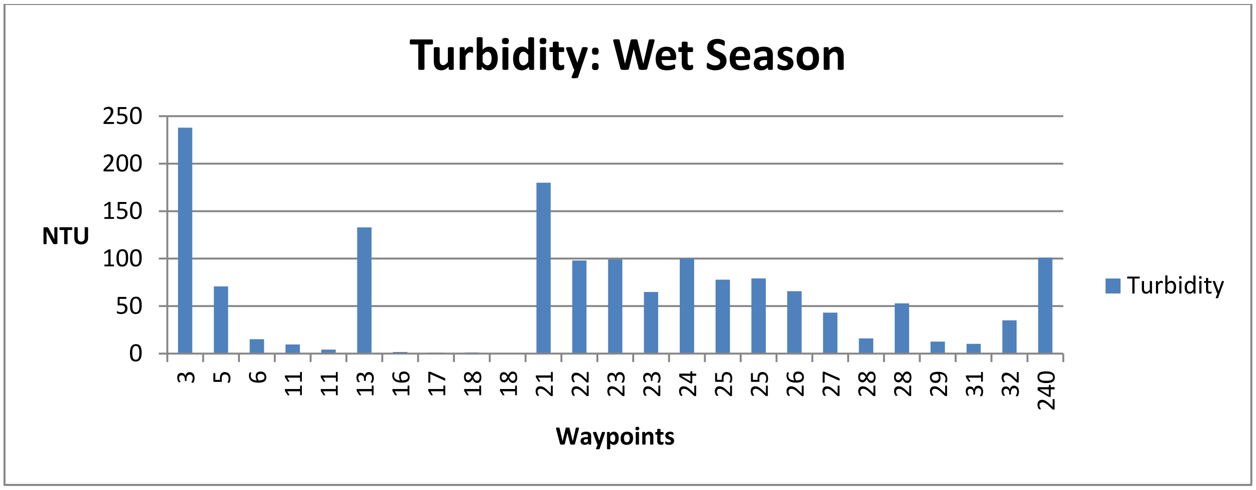

Suspended Solids: Dry Season
mg/L
60
50
40
30
20
10
0
3
3
5
5
5
6
6
6
7
8
9
10
11
11
13
13
14
15
16
16
17
17
18
18
25
27
28
29
300
Waypoints
SS

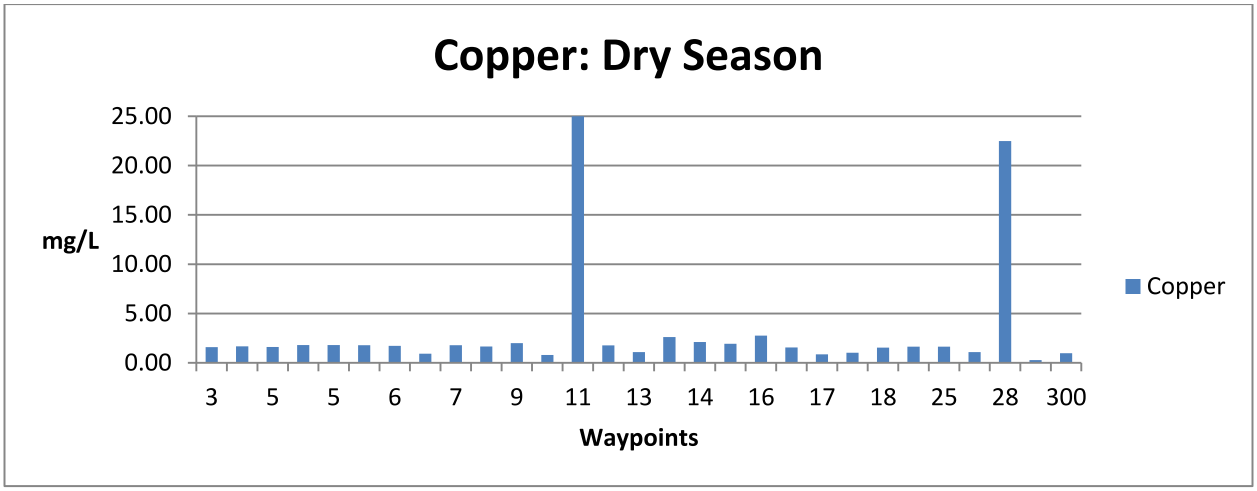

Suspended Solids: Wet Season
mg/L
250
200
150
100
50
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
SS

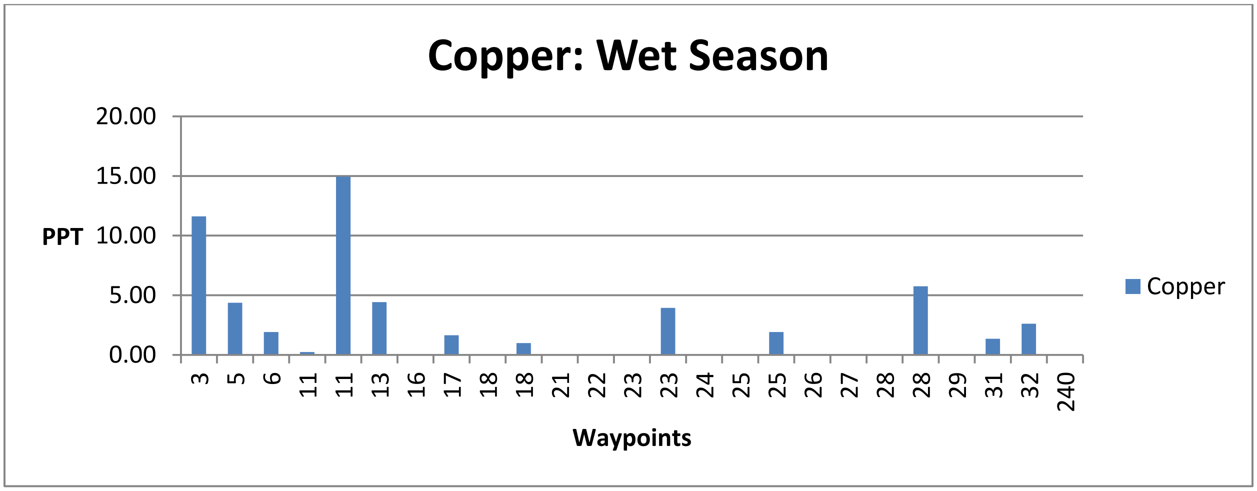

Total Dissolved Solids: Dry Season
g/L
14
12
10
8
6
4
2
0
3 3 5 5 5 6 6 6 7 8 9 10 11 11 13 13 14 15 16 16 17 17 18 18 25 27 28 29 300
Waypoints
TDS


Total Dissolved Solids: Wet Season
g/L
14
12
10
8
6
4
2
0
3 5 6 11 11 13 16 17 18 18 21 22 23 23 24 25 25 26 27 28 28 29 31 32 240
Waypoints
TDS


Turbidity: Dry Season
NTU
70
60
50
40
30
20
10
0
3 5 5 6 7 9 11 13 14 16 17 18 25 28 300
Waypoints
Turbidity


Turbidity: Wet Season
NTU
250
200
150
100
50
0
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Turbidity


Copper: Dry Season
mg/L
25.00
20.00
15.00
10.00
5.00
0.00
3
5
5
6
7
9
11
13
14
16
17
18
25
28
300
Waypoints
Copper


Copper: Wet Season
PPT
20.00
15.00
10.00
5.00
0.00
3
5
6
11
11
13
16
17
18
18
21
22
23
23
24
25
25
26
27
28
28
29
31
32
240
Waypoints
Copper

References

Ahmad, A. L., S. Ismail, and S. Bhatia. 2003. Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination* **157**:87-95.

AIP. 2011. The carbon dioxide greenhouse effect. The discovery of global warming. (http://www.aip.org/history/climate/co2.htm/%20Figure%20captionsqf.,cf.osb&fp=3ddc6ee7f452a242&biw=1011&bih=546) (accessed July 12, 2012).

Ambiente y Desarrollo Consultores, S.A. 2011. Estudio de Evaluación de Impacto Ambiental "MINERVA", promovido por la empresa Agroaceite, S.A.

American Forests. 2012. Forests and water. American Forests, Washington, D.C. (http://www.americanforests.org/conservation-programs/forests-and-water) (accessed July 12, 2012).

Baldwin, D. S., A. M. Mitchell, and J. M.Olley. 2002. Pollutant-sediment interactions: Sorption, reactivity and transport of phosphorus. *Agriculture, Hydrology, and Water Quality*, 265. CABI: New York, New York.

Bauder, T. A., R. M. Waskom, P. L. Sutherland, and J. G. Davis, J. G. 1986. Irrigation water quality criteria. Fact sheet no. 0.506. Colorado State University Extension.

Beach, T., N. Dunning, S. Luzzadder-Beach, D. E. Cook, and J. Lohse. 2006. Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands. *Catena,* **65**:166-178.

Below, R., E. Grover-Kopec, and M. Dilley. 2007. Documenting drought-related disasters: a global reassessment. *The Journal of Environmental Development* **16**:328-345.

Bennett, E. M., S. R. Carpenter, and N. F. Caraco. 2001. Human impact on erodible phosphorus and eutrophication: a global perspective. *BioScience* **51**:227–234.

Bowen, H. J. M. 1985. The natural environment and biogeochemical cycles. Pages 1-26 *in* D. Hutzinger, editor. The handbook of environmental chemistry **1** (part D). Springer-Verlag: New York.

Boyd, C. E. 1982. Water quality management for pond for fish culture. Elsevier Scientific Publishing Company: Amsterdam.

Brady, N. C. 1990. The nature and properties of soils, 10th edition. Macmillan Publishing: New York, N.Y.

Breeuwsma, A., and S. Silva. 1992. Phosphorus fertilization and environmental effects *in* The Netherlands and the Po region (Italy). The Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, Report.

Bringezu, S., H. Schütz, M. O´Brien, L. Kauppi, R. W. Howarth, and J. McNeely. 2009. Assessing Biofuels. UNEP:120. (http://www.unep.fr/scp/rpanel/pdf/Assessing_Biofuels_Full_Report.pdf) (accessed July 12, 2012).

Burcher, C. L., H. M. Valett, and E. F. Benfield. 2007. The land-cover cascade: relationships coupling land and water. *Ecology*, **88**(1):228-242.

Bureau of Meteorology. 2012. The Greenhouse Effect and Climate Change. Australian Government, Bureau of Meteorology. (www.bom.gov.au/info/GreenhouseEffectAndClimateChange.pdf)

Burkart, B. 1978. Offset across the Polochic Fault of Guatemala and Chiapas, Mexico. *Geology*, **6**:328-332.

California State Water Resources Control Board. 2001. Report in support of U.S. Environmental Protection Agency's Review of California's Continuing Planning Process (http://www.waterboards.ca.gov/water_issues/programs/ocean/docs/oplans/cpp2001.doc).

Carpenter, S.R., N. F. Caraco, D. L. Correll, R .W. Howarth, A. N. Sharpley, and V. H. Smith. 1998b. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications* **8**(3):559–568.

Carr, M. J. 1984. Symmetrical and segmented variation of physical and geochemical characteristics of the Central American volcanic front. *Journal of Volcanology and Geothermal Research* **20**:231-252.

Carr, M. J., and R. Stoiber. 1990. Volcanism. *in* The Caribbean region: The geology of North America. *Geological Society of America, Decade of North American Geology*, **H**:37-76.

Carrere, R. 2012. Oil palm: The expansion of another destructive monoculture, *in* R. Carrere and L. Lohmann, editors. The bitter fruit of oil palm: dispossession and deforestation. World Rainforest Movement:74. (http://www.wrm.org.uy/plantations/material/oilpalm2.html) (accessed July 12, 2012).

Case, J. E., T. L. Holcombe, and R. G. Martin. 1984. Map of geological provinces in the Caribbean region. *in* The Caribbean - South American plate boundary and regional tectonics: Geological Society of America, Memoir **162**:1-30.

Case, J. E., W.D. MacDonald, and P. J. Fox. 1990. Caribbean crustal provinces; seismic and gravity evidence. *in* The Caribbean region: The Geology of North America: Geological Society of America, Decade of North American Geology **H**:15-36.

Castillo, L. E., C. Ruepert, and E. Solis. 2000. Pesticide residues in the aquatic environment of banana plantation areas in the North Atlantic Zone of Costa Rica. *Environmental Toxicology and Chemistry* **19**:1942-1950.

Chambers, J. Q., G. P. Asner, D. C. Morton, L. O. Anderson, S. S. Saatchi, F. D. B. Espirito-Santo, et al. 2007. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends in Ecology & Evolution* **22**:414-423.

Chapman, D., and V. Kimstach. 1996. Selection of water quality variables i*n* D. Chapman, editor, Water Quality assessment - a guide to use of biota, sediments and water in environmental monitoring, 2nd edition. UNESCO/WHO/UNEP:609.

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

Chhabra, A., H. J. Geist, et al. 2006. Multiple impacts of land-use/cover change. Pages 71-116 *in* E. F. Lambin and H. J.Geist, editors. Land-use and land-cover change: local processes and global impacts. Springer-Verlag, Berlin.

Chiabai, A., K. Khatun, J. Martin-Ortega, and E. Ojea. 2010. Economic assessment of ecological services in tropical forests: potential for conservation policies in Central America. *ISEE Conference: Advancing Sustainability in a Time of Crisis*, 22-25 August 2010:28 (http://www.isee2010.org/paper/23ps0203%23Economic%20Assessment%20of%20Ecological%20Service%20in%20Tropical%20Forests%23_Chiabai,Aline_.pdf) (accessed July 12, 2012)

Chowdhury, R. R. 2006. Driving forces of tropical deforestation: The role of remote sensing and spatial models. *Singapore Journal of Tropical Geography* **27:**82-101.

CIA. 2012. The world factbook: Central America and Caribbean: Guatemala. (https://www.cia.gov/library/publications/the-world-factbook/geos/gt.html) (accessed July 11, 2012).

Cohen, W. B., and S. N. Goward. 2004. Landsat's Role in Ecological Applications of Remote Sensing. *Bioscience* **54**:535.

Conquest, L.L. 2000. Environmental Monitoring: Investigating Associations and Trends. Pages 179-210 in T. Sparks, *Statistics in ecotoxicology*. Wiley: Chichester, New York.

Costanza, R., R. d'Arge, S. deGroot, M. Farber, B. Grasso, K. Hannon, S. Limburg, R. Naeem, V. O'Neill, J. Paruelo, R. G. Raskin, R. Sutton, and M. vandenBelt. 1997. The value of the world's ecosystem services and natural capital. *Nature* **387**:253-260.

Davies, D.K., Querry, M.W. & Bonis, S.B. (1978). Glowing avalanches from the 1974 eruption of the volcano Fuego, Guatemala. *Geol Soc America Bull Geological Society of America Bulletin,* **89:**369-384

DeFries, R. S., J. A. Foley, and G. P. Asner. 2004. Land-use choices: balancing human needs and ecosystem function. *Frontier in Ecology and the Environment* **2**(5):249-257.

Donnelly, T. W., G. S. Horne, R. C. Finch, and E. Lopez-Ramos. 1990. Northern Central America; the Maya and Chortís blocks. *in* The Caribbean region: The Geology of North America: Geological Society of America, Decade of North American Geology.

Dosseto, A., Bourdon, B., Gaillardet, J., All©·gre, C.J. & Filizola, N. (2006). Time scale and conditions of weathering under tropical climate: Study of the Amazon basin with U-series. *Geochimica et cosmochimica acta.,* **70**:71-89.

Drakenberg, O. 2006. Poverty and environment in Guatemala. Depart of Economics, Environmental Economics unit, School of Economics and Commercial Law, Göteborg University.

Eaton, A. D., and M. A.H. Franson. 2005. Standard methods for the examination of water and wastewater. *American Public Health Association*:55.

Equities.com. 2012. Clean global energy to acquire interest in Guatemalan oil and gas projects, July 10. (http://www.equities.com/news/headline-story?dt=2012-07-10&val=254051&cat=energy) (accessed July 11, 2012).

Fagan, B. 2008. The great warming: climate change and the rise and fall of civilizations. Bloomsbury Press: New York, NY.

FAO. 2000. World soil resource report 90. land resource potential and constraints at regional and country levels. Land and Water Resource Division, UN FAO: Rome, Italy.

FAO. 2003. The state of food insecurity in the world 2003. FAO Water Resources Development and Management Service (2003) AQUASTAT Information System on Water and Agriculture. Review of World Water Resources by Country. UN FAO, Rome, Italy. (www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat/water_res/index.htm).

FAO. 2008. The global remote sensing survey. (http://www.fao.org/forestry/fra/remotesensingsurvey/en/) (accessed July 15, 2012)

FAO. 2010. Global forest resources assessment 2010. (www.fao.org/forestry/fra/fra2010/en) (accessed July 11, 2012)

Fipps, G., J. McAfee, J., and Texas Cooperative Extension. 2004. *Turf irrigation and nutrient management : Reference manual*. Texas Cooperative Extension, Texas A & M University System: College Station, TX.

Foley, J. A., R. DeFries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, et al. 2005. Global Consequences of Land Use. *Science* **309**:570-574.

Foody, G. M. 2002. Status of land cover classification accuracy assessment. *Remote Sensing of Environment* - New York **80**:185-201.

Fosdick, J. C., et al. 2005. Field guide to 2004-2005 Guatemalan geology Stanford alpine Project. Department of Geological and Environmental Sciences, Stanford University.

Franklin, S.E., Lavigne, M.B., Deuling, M.J., Wulder, M.A. & Hunt, E.R. (1997). Estimation of forest Leaf Area Index using remote sensing and GIS data for modeling net primary production. *International Journal of Remote Sensing,* **18**:3459-3471.

Freudenthal, H.1965. Probability and statistics. Elsevier Pub. Co., Amsterdam; New York.

Friday, F. A. 1967. The elements of probability and sampling. Blackwell, Oxford, UK.

Fung, T. & Siu, W. (2000). Environmental quality and its changes, an analysis using NDVI. *International Journal of Remote Sensing,* **21**:1011-1024.

Gardner, R. H. 2001. Scaling relations in experimental ecology. Columbia University Press: New York.

Geist, H. J., and E. F. Lambin. 2004. Dynamic causal patterns of desertification. *Bioscience* **54**: 817-829.

Gerbens-Leenes, P. W., A. Y. Hoesksra, and van der Meer, 2009, The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecological Economics* **68**:1052-1060.

German, L., G. Schoneveld, M. Skutch, R. Andriani, K. Obidzinski, P. Pacheco, H. Komarudin, A. Andrianto, M. Lima, and A.A.B. Dayang Norwana. 2010. The local social and environmental impacts of biofuel feedstock expansion: a synthesis of case studies from Asia, Africa and Latin America. Infobrief, CIFOR **34**:12.

Gleick, P. H., 2008, Water conflict chronology: Database on water and conflict (water brief). Pacific Institute for Studies in Development, Environment and Security (11 October 2008, updated 11/09). (http://www.worldwater.org/conflict.html) (accessed July 12, 2012).

Gorte, R. W. 2009. Carbon sequestration in forests. Congressional Research Service.

Griffith, J. A. 2002. Geographic techniques and recent applications of remote sensing to landscape-water quality studies. *Water, Air, and Soil Pollution* **138:** 181–197, 2002.

Gruhn, P., F Goletti,. and M. Yudelman. 2000. Integrated nutrient management, soil fertility and sustainable agriculture: current issues and future challenges. Food, agriculture and the environment discussion paper 32. International Food Policy Research Institute: Washington, D.C.

Gunlu, A., E. Başkent, A. Kadıoğulları, and L. Altun. 2009. Forest site classification using Landsat 7 ETM data: A case study of Maçka-Ormanüstü forest, Turkey. *Environmental monitoring and assessment* **151**:93-104.

Hall, F. G., D. B. Botkin, D. E. Strebel, K. D. Woods, and S. J. Goetz. 1991. Large-scale patterns of forest succession as determined by remote sensing. *Ecology* **72**(2):628-640.

Hartter, J., and J.Southworth. 2009. Dwindling resources and fragmentation of landscapes around parks: wetlands and forest patches around Kibale National Park, Uganda. Springer: Netherlands.

Haygarth, P. M., and S. C. Jarvis, editors. 2002. Agriculture, hydrology and water quality: CABI Publishing, UK / NY, USA.

Henriques, W., R. D. Jeffers, T. E. Lacher, and R. J. Kendall. 1997. Agrochemical use on banana plantations in Latin America: Perspectives on ecological risk. *Environmental Toxicology and Chemistry* **16**:91-99.

Hesterberg, T., S. Monaghan, D. S. Moore, A. Clipson, and R. Epstein. 2003. Bootstrap methods and permutation tests: Companion chapter 18 to The practice of business statistics: W. H. Freeman and Company: New York.

Higbee, E. C. 1947. The agricultural regions of Guatemala. Geographical Review 37(2):177-201.

Hill, A. R. 1996. Nitrate removal in stream riparian zones. Journal of Environmental Quality **25**:743–755.

Hillel, D. J. 1991. Out of the Earth: Civilization and the life of the soil: The Free Press: New York, N.Y.

Hoekstra, A. Y., and A. K. Chapagain. 2007. Water footprints of nations: water use by people as a function of their consumption patterns. *Water Resource Management* **21**:35-48.

Hoekstra, A. Y., and P. Q. Hung. 2002. Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade: Value of water research report series, no. 11. ENESCO-IHE, Delft, The Netherlands (www.waterfoot-print.org).

Humbert, S. 2010. Water footprinting, life cycle assessment, and standardization: Consultative workshop on water footprint, neutrality and efficiency, Osaka Japan, 1-3 June 2010 (gec.jp/gec/en/Activities/ietc/fy2010/wf/wf_s3-2.pdf) (accessed July 12, 2012).

Hutzinger, O., and H. J. M. Bowen. 1985. The handbook of environmental chemistry. Springer: Berlin.

Index Mundi. 2012. Guatemala cotton production by year (http://www.indexmundi.com/agriculture/?country=gt&commodity=cotton&graph=production) (accessed July 20, 2012).

Jara, M.C. 2010. ABC of Climate Change in MesoAmerica. Tropical Agriculture Research and higher Education Center (CATIE).

(http://www.catie.ac.cr/BancoMedios/Documentos%20PDF/abc%20ingles.pdf)
(accessed June 30 2012).

Jensen, J. R. 1996, Introductory digital image processing**:** A remote sensing perspective. Prentice-Hall: New Jersey.

Jensen, J. R. 2006. Remote Sensing of the Environment: an Earth Resources Perspective, 2nd edition Prentice-Hall: New Jersey.

Jones, H. G., and Vaughan, R. A. 2010. Remote sensing of vegetation: principles, techniques, and applications. Oxford University Press: Oxford/New York.

Kansas Collaborative Research Network (KanCRN). 2012.Water quality index: calculating a WQI. http://kancrn.org/stream/cp4wqi.cfm.

Kitchin, K. T., and R. Conolly. 2010. Arsenic-induced carcinogenesis-oxidative stress as a possible mode of action and future research needs for more biologically based risk assessment. *Chemical Research in Toxicology* **23**:327-335.

Kok, K. & Veldkamp, A. (2001). Evaluating impact of spatial scales on land use pattern analysis in Central America. *Agriculture Ecosystems and Environment,* **85**, 205-221.

Kreuter, U. P., H. G. Harris, M. D. Matlock, R. E. Lacey. 2001. Change in ecosystem service values in the San Antonio area, Texas. Ecological Economics **39**:333-346.

Lambin, E. F. 1999. Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. *Global Ecology and Biogeography* **8**:191-198.

Lambin, E.F., and H. Geist. 2006. Land-use and land-cover change: local processes and global impacts. Springer: Berlin/New York.

Lambin, E. F., B. L. Turner, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce, et al. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* **11**:261-269.

Langner, A., J. Miettinen, J., and F. Siegert. 2007. Land cover change 2002-2005 in Borneo and the role of fire derived from MODIS imagery. *Global Change Biology* **13**:2329-2340.

Laurance, W. F. 1999. Reflections on the tropical deforestation crisis. *Biological Conservation* **91**:109-117.

Lee, D.J. & Howitt, R.E. (1996). Modeling Regional Agricultural Production and Salinity Control Alternatives for Water Quality Policy Analysis. *American Journal of Agricultural Economics* **78**: pp. 41-53.

Lu, D. (2005). Integration of vegetation inventory data and Landsat TM image for vegetation classification in the western Brazilian Amazon. *Forest Ecology and Management* **213**:369-383.

Lundin, M., and G. M. Morrison. 2002. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. *Urban Water* 4:145-152.

Lyns Ltd., 2012, Pyrolysis fuel system. Lyns Ltd. (http://www.wasterecycleplant.com/pyrolysis_fuel_system.html) (accessed July 12, 2012)

Malthus, T. R.. 1798, An essay on the principle of population, as it affects the future improvement of society, 1st edition, Penguin Classics: London. (www.econlib.org/library/Malthus/malPop.html) (accessed February 3, 2012).

Mann, P., R. Rogers, and L. Gahagan. 2006. Overview of plate tectonic history and its unsolved tectonic problem. Pages 205-241 *in* J. Buncdschud, editor. Central America: geology, resources, and natural hazards, chapter 8. Balkema Publishers: The Netherlands.

MARN. 2004**.** *Climate Change Studies in Guatemala with emphasis on Adaptation*, Ministry of the Environment and Natural Resources, National Climate Change Program, Guatemala. (http://www.nlcap.net/fileadmin/NCAP/Countries/Guatemala/NCAP_workplan_Guatemala_summary.01.300106.pdf) (accessed July 2, 2012).

Mapa Munda, CIA. 1983. Guatemala industry and agriculture. (http://www.zonu.com/detail-en/2009-09-17-1326/Guatamala-Industry-and-Agriculture-1983.html) (accessed July 20, 2012).

Maloney K. O., and D. E. Weller. 2011. Anthropogenic disturbance and streams: Land use and land-use change affect stream ecosystems via multiple pathways. *Freshwater Biology* **56**:611-626.

Matson, P. 1997. NOx emissions from soils and its consequences for the atmosphere and biosphere. *Nutrient Cycling in Agroecosystems* **48**:1-6.

Matson, P. A., W. J. Parton, A. G. Power, and M. Swift. 1997. Agricultural intensification and ecosystem properties. *Science* **277**:504-509.

MEA. 2003. Ecosystem and human well-being: A framework for assessment. Island Press: Washington, DC.

MEA. 2005. Millennium ecosystem assessment: ecosystems and human well-being synthesis. findings of the condition and trends working group of the millennium ecosystem assessment. Island Press: Washington, D.C.

Mertens, B., and E. F. Lambin. 1997 Spatial modeling of deforestation in Southern Cameroon: Spatial disaggregation of diverse deforestation processes. *Applied Geography* **12:**143-162.

Mertens, B., and E. F. Lambin. 2000. Land-Cover-Change Trajectories in Southern Cameroon. *Annals of the Association of American Geographers* **90**:467-494.

Meybeck, M. 1982. Carbon, nitrogen and phosphorus transport by world rivers. *American Journal of Science* **282**:401-450.

Miller, D. A., R. A. White. 1998. A conterminous United States multilayer soil characteristics dataset for regional climate and hydrology modeling. *Earth Interact* **2:**1–26.

Mitchell, M. K. and W. B. Stapp. 1994. Field manual for water quality monitoring. Eighth edition. Thomson-Shore, Inc.: Dexter, Michigan.

Mongabay.com. 2012. Guatemala forest information and data. (http://rainforests.mongabay.com/deforestation/2000/Guatemala.htm) (accessed July 11, 2012).

Moss B (2008). Water pollution by agriculture. *Philosophical transactions of the Royal Society of London, Series B, Biological Sciences* **363**:659-66.

Mousdale, D. M. 2008. Biofuels. biotechnology, chemistry and sustainable development: CRC Press, Taylor & Francis Group: Boca Raton, FL.

Muehlberger, W. R. 1992. 1996. Tectonic map of North America: American Association of Petroleum Geologists:2 sheets.

Mutanga, O., and A. K. Skidmore. 2004. Narrow band vegetation indices overcome the saturation problem in biomass estimation. *International Journal of Remote Sensing* **25**:3999-4014.

Nagendra, H., J. Southworth, and C. Tucker. 2003. Accessibility as a determinant of landscape transformation in western Honduras: linking pattern and process. *Landscape Ecology* **18**:141-158.

NASA Earth Observatory. Measuring vegetation. (http://earthobservatory.nasa.gov/Features/MeasuringVegetation/measuring_vegetation_2.php) (accessed January 3, 2012).

Neff, H., D. M. Pearsall, J. G. Jones, B. Arroyo, S. K. Collins, and D. E. Freidel. 2006. Early Maya Adaptive Patterns: Mid-Late Holocene Paleoenvironmental Evidence from Pacific Guatemala. *Latin American Antiquity* **17**:287-315.

Neilson, R.P., and S.W. Running, 1996, Global dynamic vegetation modeling: coupling biogeochemistry and biogeography models. *Global Change and Terrestrial Ecosytems* **23**:451-465.

Nemani, R. R., and S. W. Running. 1989. Estimation of surface resistance to evapotranspiration from NDVI. *Journal of Applied Meteorology* **28**:276.

Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). 2011. MODIS subsetted land products, Collection 5. Available on-line [http://daac.ornl.gov/MODIS/modis.html] from ORNL DAAC, Oak Ridge, Tennessee, U.S.A. Accessed November, 2012.

Okin, G. S., and Roberts, D. A., 2004. Remote Sensing in Arid Regions: Challenges and Opportunities. In Ustin, S. L., and American Society for Photogrammetry and Remote Sensing. *Remote sensing for natural resource management and environmental monitoring*. John Wiley & Sons: Hoboken, NJ.

Okwute, L., and N. R. Isu. 2007, The environmental impact of palm oil mill effluent (pome) on some physico-chemical parameters and totalaerobic bioload of soil at a dump site in Anyigba, Kogi State, Nigeria. *African Journal of Agriculture* 2(12):656.

Pal, M., and P. M. Mather. 2003. An assessment of the effectiveness of decision tree methods for land cover classification. *Remote Sensing of Environment,* **86**:554-565.

Ongley, E .D. 1996. Control of water pollution from agriculture: UN FAO, Rome.

Pal, J. S., et al. 2007. Regional climate modeling for the developing world. The ICTP RegCM3 and RegCNET:15. (www.stanford.edu/~omramom/Pal_BAMS_07.pdf) (accessed July 11, 2012).

Reese, H., M. Nilsson, T. G. Pahlen, O. Hagner, S. Joyce, U. Tingelof. et al. 2003. Countrywide Estimates of Forest Variables Using Satellite Data and Field Data from the National Forest Inventory. *AMBIO: A Journal of the Human Environment,* **32**:542-548.

Rejmankova, E., H. M. Savage, M., Rejmanek, D. R. Roberts, and J. I. Arredando-Jimenez. 1991. Multivariate analysis of relationships between habitats, environmental factors and occurrence of anopheline mosquito larvae (*Anopheles albimanus* and *A. pseudopunctipennis*) in southern Chiapas, Mexico. *Journal of Applied Ecolog*y **28**(3):827-841.

Ribeiro, D.B., P. I. Prado, K. S. Brown, Jr., and A. V. L. Freitas. 2008. Additive partitioning of butterfly diversity in a fragmented landscape: importance of scale and implications for conservation. *Diversity and Distributions* **14**:961-968.

Rose, W.I., Anderson, A.T., Jr., Woodruff, L.G., and Bonis, S.B. 1978. The October 1974 Basaltic Tephra from Fuego Volcano: description and history of the magma body. *J. Volcanology. Geothermal Research* **4**:3-53.

Rose, W.I., Stoiber, R.E., and Malinconico, L.L. 1982. Eruptive gas compositions and fluxes of explosive volcanoes: budget of S and Cl emitted from Fuego volcano, Guatemala, In: Thorpe RS (ed) Andesites: Orogenic Andesites and Related Rocks, John Wiley and Sons: Chichester, England.

Sanchez, P.A. 1976., Properties and management of soils in the tropics. Wiley: New York, N.Y.

Scaramuzza, P., E. Micijevic, and G. Chander. 2004. *SLC Gap-Filled Prducts Phase One Methodology*. United States Geological Survey.

Schloss, A. L., D. W. Kicklighter, J. Kaduk, U. Wittenberg, and Intercomparison, T.P.O.T.P.N.M. 1999. Comparing global models of terrestrial net primary productivity (NPP): comparison of NPP to climate and the Normalized Difference Vegetation Index (NDVI). *Global Change Biology* **5**:25-34.

Schmidt, J., V. Gass, and E. Schmid. 2011. Land use changes, greenhouse gas emissions and fossil fuel substitution of biofuels compared to bioelectricity production for electric cars in Austria. *Biomass and Bioenergy* **35**:4060-4074.

Schulz, R., and S. K. Peall. 2001. Effectiveness of a constructed wetland for retention of nonpoint-source pesticide pollution in the Lourens River catchment, South Africa. *Environmental Science & Technology* **35**:422– 426.

Schweik, C.M., Nagendra, H. & Sinha, D.R. (2003). Using Satellite Imagery to Locate Innovative Forest Management Practices in Nepal. *AMBIO: A Journal of the Human Environment* **32**: 312-319.

Sedell, J., Sharpe, M., Dravieks-Apple, D., Copenhagen, M. and Furniss, M. 2000. Water and the Forest Service. FS-660. U.S. Department of Agriculture, Forest Service: Washington, DC.

Setiono, B. 2008. Corruption and forest revenues in Papua. CMI, Anti-Corruption Resource Centre, www.U4.no **18**: 4 (accessed July 11, 2012).

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing Agricultural Phosphorus for Protection of Surface Waters: Issues and Options. *Journal of environmental quality* **23**:437-451.

Simmons, C. S., J. M. Tarano, and J. Humberto Pinto. 1959. Classificacion de reconocimiento de los suelos de la Republica de Guatemala. Ministerio de Agricultura: 2 sheets.

Smith, J.L., Collins, H.P. & Bailey, V.L. (2010). The effect of young biochar on soil respiration. *Soil Biology and Biochemistry* **42**:2345-2347.

Southworth, J., and C. Gibbes. 2010. Digital Remote Sensing within the Field of Land Change Science: Past, Present and Future Directions. *Geography Compass* **4**:1695-1712.

Southworth, J., D. Munroe, and H. Nagendra. 2004. Land cover change and landscape fragmentation—comparing the utility of continuous and discrete analyses for a western Honduras region. *Agriculture, Ecosystems & Environment* **101**:185-205.

Southworth, J., and C. M Tucker. 2001. Forest cover change in western Honduras: the role of socio-economic and biophysical factors, local institutions, and land tenure. *Mountain Research and Development* **21**:276-283.

Stecker, T., and Climate Wire. 2012. Climate models spell hard times for tropical farmers. *Scientific American* **February 24**:2. (http://www.scientificamerican.com/article.cfm?id=climate-models-spell-hard-times-tropical-farmers) (accessed July 11, 2012).

Suntana, A. S., K. A. Vogt, E. C. Turnblom, and R. Upadhye. 2009. Bio-energy potential in Indonesia: forest biomass as a source of biofuels that reduces carbon emissions. *Applied Energy* 86 (supplement 1):S215-S221.

Tanji, K. K. 1990. Nature and extent of agricultural salinity (chapter 1) *in* K.K. Tanji, editor, Agricultural salinity assessment and management, ASCE Manual No. 71, American Society of Civil Engineers: New York.

Tenenbaum D.J. (2008). Food vs. fuel diversion of crops could cause more hunger. *Environ.Health Perspect.Environmental Health Perspectives* **116**:A254.

Tomppo, E. 1991. Satellite image-based national forest inventory of Finland. Proceedings of the symposium on global and environmental monitoring, techniques and impacts (Victoria, British Columbia, Canada, 17–21 September 1990). *International Archives of Photogrammetry and Remote Sensing* **28** (1–7): 419−424).

Tomppo, E., H. Olsson, G. Stahl, M. Nilsson, O. Hagner, and M. Katila. 2008. Combining national forest inventory field plots and remote sensing data for forest databases. *Remote Sensing of Environment* **112**:1982-1999.

Townsend C. R., S. Doledec, R. Norris, K. Peacock, and C. Arbuckle. 2003. The influence of scale and geography on relationships between stream community composition and landscape variables:description and prediction. *Freshwater Biology* **48**:768–85.

Trading Economics. 2012. Agricultural Land (% of Land area) in Guatemala: http://www.tradingeconomics.com/guatemala/agricultural-land-percent-of-land-area-wb-data.html (accessed July 11, 2012).

Tuinstra, N. A. 2008. Sustainability analysis of African palm biodiesel in Ecuador: an environmental, socio-cultural, and artistic perspective. Bachelors, Honors Oregon State University, 2008. Print. Corvalis, Oregon.

Turner, D. P., W. B. Cohen, R. E. Kennedy, K. S. Fassnacht, and J. M. Briggs. 1999. Relationships between Leaf Area Index and Landsat TM Spectral Vegetation Indices across Three Temperate Zone Sites. *Remote Sensing of Environment* **70**:52-68.

U.S. EPA. 1990. Water quality standards for wetlands: national guidance, Appendix D: Water Quality Standards Handbook 2nd edition. (http://water.epa.gov/scitech/swguidance/standards/upload/2002_06_11_standards_handbook_handbookappxD.pdf**)**.

U.S. EPA. 2006. National recommended water quality criteria. (http://yosemite.epa.gov/water/owrccatalog.nsf/7322259e90d060c885256f0a0055db68/f81c2556905f48888525730d00517315!OpenDocument)

Uriarte, M., C. Yackulic, Y. Lim, and J. Arce-Nazario. 2011. *Influence of land use on water quality in a tropical landscape: a multi-scale analysis*. Springer: Netherlands.

Ustin, S. L., and American Society for Photogrammetry and Remote Sensing. 2004. *Remote sensing for natural resource management and environmental monitoring*. John Wiley & Sons: Hoboken, NJ.

Vellidis, G., G. R. Lowrance, P. Gay, and R. K. Hubbard. 2002. Nutrient transport in a restored riparian wetland: Journal of Environmental Quality **32**(2):711-726.

Vidgen, L. and Schechter, D. C. 2010. *Guatemala.* Lonely Planet, Footscray, Vic.: London.

Vogt, K. A. 1997. *Ecosystems : Balancing science with management*. Springer: New York.

Vogt, D. J., K. A. Vogt, J. C. Gordon, M. L. Miller, C. Mukumoto, R. Upadhye, and M. H.. Miller. 2009. Wood methanol as a renewable energy source in some western states. *in* B. Solomon and V. A. Luzadis, editors. Renewable energy from forest resources in the United States. Routledge Publishing, Taylor & Francis Group: London and New York, N.Y.

Vogt, K. A., D. J. Vogt, T. Patel-Weynand, R. Upadhye, D. Edlund., C. Gordon, A. S. Suntana, R. L. Edmonds, R. Sigurdardottir, P. A. Roads, and M. G. Andreu. 2008. Why forest derived biofuels can mitigate climate change: the case for C-based energy production. Renewable Energy **34**:233-241.

Vogt, K. A., D. J.Vogt, M. Shelton, T. Colonnese, L. Stefan, R. Cawston, J. Scullion, M. Marchand, R. K. Hagmann, M. Tulee, L. Nackley, T. C. Geary, T. A. Houste, S. Candelaria, I. Nwaneshiudu, A. M. Lee, E. Kahn, L. L. James, S. J.Rigdon, R. M. Theobald, and L. X. Lai. 2010a. Bio-resource based energy for sustainable societies. *in* W. H. Lee and V. G. Cho, editors. Handbook of sustainable energy. Nova Science Publishers Inc.: Hauppauge, N.Y.

Vogt, K. A., T. Patel-Weynand, M. Shelton, D. J. Vogt, J.C. Gordon, C. T. Mukumoto, A. S. Suntana, and P. A. Roads, P.A.2010b. Sustainability unpacked: food, energy and water for resilient environments and societies: Earthscan Ltd.: London, Washington, D.C.

Vogt, K. A, Scullion J.J., Nackley, LL. and Shelton, M. 2012. Conservation efforts, contemporary. *In*: (S. Levin, ed.) Encyclopedia of biodiversity. 2nd Edition. Academic Press: N.Y.

Vogt, K.A., Daniel J. Vogt, Toral Patel-Weynand and Ravi Upadhye.. 2009. Bio-methanol: How energy choices in the western United States can help mitigate global climate change. *Renewable Energy* **34**:233-241.

Vogt, K.A., Andreu, M.G., Vogt, D.J., Sigurdardottir, R., Edmonds, R.L., Schiess, P. *et al.* (2005). Societal Values and Economic Return Added for Forest Owners by Linking Forests to Bioenergy Production. *Journal of Forestry-Washington* **103**:21-27.

Wernberg, T., and N. Goldberg. 2008. Short-term temporal dynamics of algal species in a subtidal kelp bed in relation to changes in environmental conditions and canopy biomass. *Estuarine, Coastal and Shelf Science* **76**:265-272.

Wessels, K. J., S. D. Prince, and I. Reshef. 2008. Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. *Journal of Arid Environments* **72**:1940-1949.

West, B. 2005. Prescribed burning in southern pine forests: Fire ecology, techniques, and uses for wildlife management: Mississippi State University Extension Service. (msucares.com/pubs/publications/p2283.pdf) (accessed July 12, 2012).

Weyl, R. 1980. Geology of Central America, 2nd edition. Gebruder Borntraeger: Berlin.

Wild, A. 1993. Soils and the environment. an introduction: Cambridge University Press: Cambridge, UK.

Wood, C. H., and D. L. Skole. 1998. Linking satellite, census and survey data to study deforestation in the Brazilian Amazon.Pages 70-93 *in* D. Liverman, E. F. Moran, R. R. Rindfuss, and P. C. Stern editors, People and pixels: linking remote sensing and social science. National Academy Press: Washington, DC.

World Bank. 2009. *Climate risk and adaptation country profile.* (www.worldbank.org/lacagccnotes) (accessed July 2, 2012) .

World Health Organization (WHO). 2004. Guidelines for drinking water quality. Geneva.

World Health Organization (WHO). 2008. Guidelines for Drinking-water Quality: Third Edition, Incorporating the First and Second Addenda: Geneva.

World Bank. 2009. Climate risk and adaptation country profile. Guatemala: Country Note on Climate Change Aspects in Agriculture.(www.worldbank.org/lacagccnotes). (accessed July 1, 2012).

World Bank. 2011. World Bank: Climate Change Portal. (http://sdwebx.worldbank.org/climateportalb/home.cfm?page=country_profile&CCode=GTM) (accessed July 2, 2012).

World Rainforest Movement. 2012. Palm oil plantations. (http://www.wrm.org.uy/) (accessed July 3, 2012).

Worldwatch Institute. 2012. Global palm oil demand fueling deforestation. Worldwatch Institute. (http://www.worldwatch.org/node/6059) (accessed July 12, 2012).

World Wildlife Fund. 2012."Palm Oil: environmental impacts. World Wildlife Fund.. (http://wwf.panda.org/what_we_do/footprint/agriculture/palm_oil/environmental_impacts). (accessed June 2012)

Xu, C., Y. Li, J. Hu, X. Yang, S. Sheng, and M. Liu. 2012. Evaluating the difference between the normalized difference vegetation index and net primary productivity as the indicators of vegetation vigor assessment at landscape scale. *Environmental monitoring and assessment,* **184**:1275-1286.

Zalidis, G. C., T. L. Crisman and P. A. Gerakis, editors. 2002. Restoration of Mediterranean wetlands. Hellenic Ministry of Environment, Physical Planning and Public Works, Athens and Greek Biotope/Wetland Centre. Thermi:237.

Zar, J. H. 1999. *Biostatistical Analysis*. Prentice Hall: Upper Saddle River, N.J.

Zheng, L., and M. J. Paul. 2006. Effects of eutrophication on stream ecosystems: Tetra Tech, Inc. (http://n-steps.tetratech-ffx.com/PDF&otherFiles/literature_review/Eutrophication%20effects%20on%20streams.pdf) (accessed July 12, 2012).

Curriculum Vitae

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Education

PhD, School of Environment and Forest Sciences University of Washington, Seattle, WA	December 2012
Restoration Ecology Certificate Coursework and Biology Teaching University of Washington, Seattle, WA	2005 - 2007
Environmental science classes in the Professional Practitioners Program IslandWood Environmental Learning Center, Bainbridge Island, WA	2003 - 2004
Teaching Certificate Seattle University, Seattle, WA	1989 - 1990
Master of Science, Economics Baylor University, Waco, TX	1978
Bachelor of Business Administration, Economics and Finance Baylor University, Waco, TX	1977

Teaching Experience

2012	Teaching Assistant, Center for Quantitative Science, University of Washington - QSCI 482, Statistical Inference in Applied Research
2012	Research Assistant, NASA-funded Global Climate Change Education (GCCE) project. Developed experiential curriculum for high school teachers to teach *Atmospheric Science 211: Climate and Climate Change*. This program is collaboration between the UW Departments of Oceanography and Atmospheric Science, the UW Program on Climate Change and UW Educational Outreach.
2011	Teaching Assistant, Center for Quantitative Science, University of Washington - QSCI 482, Statistical Inference in Applied Research
2008 - 2009	Teaching Assistant, School of Forest Resources, University of Washington - ESRM 100, Introduction to Environmental Science - ESRM 101, Forest and Society - ESRM 201, Pacific Northwest Ecosystems - ESRM 409, Soil Ecology

2003 - 2007	Naturalist, Camp Long and Seward Park Environmental Learning Centers, Seattle, WA. Volunteer for IslandWood Environmental Learning Center. Provided stream study education for Seattle Public Schools.
1990 - 2000	Middle School Teacher, Seattle, Northshore and Tahoma School Districts, Seattle, WA Taught math, science, special education; coached track; instructed ropes course.
1987 - 1988	Teacher, Philippine Refugee Processing Center, Bataan, Philippines Taught English, math, and soccer to high school age S.E. Asian refugees in the process of resettlement.

Dissertation – Land-Use Changes in Southwest Guatemala: Assessment of their Effects and Sustainability

My dissertation examines the changes in land-use and land-cover dynamics for an area in Guatemala over the past ten years. Large plantations of African palm and banana have been making major alterations to the ecosystem in Western Guatemala. I combine geospatial data derived from satellite images with available ground data in order to measure and assess the changes over time.

Research Interests

My research interests revolve around understanding and analyzing the driving forces (economic, social, climate) behind land-cover dynamics and trajectories of land-cover change. Assessing these dynamics requires the use of analytical tools that include geospatial analysis, remote sensing, life cycle analysis, ecosystem valuation, time series analysis, and statistical inference.

Interdisciplinary Research Projects

2010 - 2012	Center for Human Rights research group, a multi-disciplinary team of UW researchers investigating the impacts of African Palm and banana plantations on local communities in Western Guatemala. - Conducted water quality and hydrological studies in Guatemala - Guided undergraduate geography students in course project for creating maps of the area of interest in Guatemala
2010 - 2011	National Science Foundation Bioenergy IGERT fellow. Worked in team of forestry and engineering students to design and prototype a portable biochar device.

Other Employment Experience

1979 - 1987	Economics and financial analysis. Seafirst Bank and Rainier Bank, Seattle, WA; First National Bank, Tulsa, OK.
1977 - 1978	Regional planner. Council of Governments, Waco, TX.

Publications

Books

Vogt, Krisitiina, Patel-Weynand, Toral, **Shelton, Maura**, Vogt, Dan, Gordon, John, Mukumoto, Calvin, Suntana, Asep, and Roads,Particia. *Sustainability Unpacked: Food, Energy and Water for Resilient Environments and Societies*. Earthscan Press, August 2010.

Publications

- Vogt, Kristiina, Vogt, Dan, **Shelton, Maura**, Colonnese, Thomas, Stefan, Laurie, Cawston, Rodney, Scullion, Jason, and Marchand, Michael. *Bio-resource Based Energy for Sustainable Societies*. Nova Science Publishers, Inc., Hauppauge, NY, January 2010.
- Vogt, KA, JJ Scullion, LL. Nackley and **M Shelton**. 2011. Conservation Efforts, Contemporary. *In*: (S. Levin, ed.) Encyclopedia of Biodiversity. 2nd Edition. Academic Press

Work In Progress

- Shelton, Maura , Godoy, Angelina, Faires, Kenneth. “Land Use Change in Guatemala: Effects of Plantations on Water Quality and Land Productivity.” (revising for submission)

Presentations

- “Sustainable Biofuels from Forest.” 3rd World Congress on Biotechnology; Dalian, China; July 25-27, 2010.
- “Bioenergy and Forest Waste.” Partnership on Tribal and Rural Education with Energy Business Enterprises; ATNI Energy; Warm Springs, OR; June 6-9, 2010.
- “Creating Tribally Compatible Green Energy Enterprises.” ATNI Energy Training; ATNI Mid-Year Conference; Grand Ronde, Oregon; May 19, 2010.

Poster Sessions

- “Land Cover and Land Use Change in Guatemala: Effects of Plantations on Land Productivity.” University of British Columbia Graduate Forestry Symposium; Vancouver, British Columbia; February 24, 2012.
- “Land Use Change in Guatemala: Effects of Plantations on Water Quality and Land Productivity.” Water Symposium; Seattle, Washington; April 19, 2012.

Patent Pending

Blanket Pyrolysis System” [IP: 45487.01US1].

Fellowships, Honors and Awards

National Science Foundation’s Integrative Graduate Education and Research Traineeship (IGERT) Program, Bioresource Based Energy for Sustainable Societies, 2009-2011.

University of Washington Foster School of Business Environmental Starbucks Prize, 2011. In recognition of the UW Bioenergy IGERT Cohort Three’s work in on a pyrolysis blanket, an innovative solution to the problem of forest residue.

School of Environment and Forest Sciences Scholarship, 2012.

Professional Organizations

Society for Ecological Restoration
XI Sigma Pi (Honorary Forestry Society)
American Society for Photogrammetry and Remote Sensing (ASPRS)
Engineers Without Borders