AN EXPLORATORY STUDY OF THE SPATIAL DISTRIBUTION OF MADAGASCAR'S DEFORESTATION AND FOOD INSECURITY

by

LEAH A. SANDMANN

(Under the Direction of Marguerite Madden)

ABSTRACT

Although deforestation and food shortages in Madagascar have been thoroughly studied independently, their connections have yet to be investigated. This research aims to explore the relationships between deforestation and food insecurity in Madagascar using a geographic information system (GIS) to model spatial variables related to national land cover, food access, and human health. Based on the United States United States Agency for International Development (USAID) conceptual framework, a new Madagascar Food Insecurity Index (FII) model was created. It contains aspects of social, physical, and biological phenomena that intersect in geographic space to produce insecurity in food access, availability, and utilization. The Madagascar FII model result identified the most food insecure areas as being in the eastern portion of the country.

INDEX WORDS: Geographic information system, Spatial modeling, Food insecurity, Deforestation, Madagascar

AN EXPLORATORY STUDY OF THE SPATIAL DISTRIBUTION OF MADAGASCAR'S DEFORESTATION AND FOOD INSECURITY

by

LEAH A. SANDMANN

B.S., The United States Military Academy, 2003

A Thesis Submitted to the Graduate Faculty of the University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2010

AN EXPLORATORY STUDY OF THE SPATIAL DISTRIBUTION OF MADAGASCAR'S

DEFORESTATION AND FOOD INSECURITY

by

LEAH A. SANDMANN

Major Professor: Marguerite Madden

Committee: Tommy Jordan
Xiaobai Yao

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
May 2010

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION, RESEARCH OBJECTIVES, AND STUDY AREA

Introduction

Pictures of charming baby lemurs are an effective way to convince a tourist to donate money to an environmental campaign. By equating the destruction of endearing tiny primates to deforestation, many people are driven to contribute to the Malagasy biodiversity and conservation causes (Figure 1.1). While Madagascar is globally known for its unique flora and fauna, its indigenous people and their plight are often overlooked. More than two thirds of the roughly 20 million Malagasy consume less than 2133 calories per day, and in 2006 approximately 72 percent of the population lived below the poverty line of 1 US dollar per day (Dostie *et al.*, 2002; WFP Madagascar, 2006). A critical contributor to the substandard living conditions is the lack of food, a basic human and societal need. Although deforestation and food shortages in Madagascar have been thoroughly studied independently, their connections have yet to be investigated. Therefore, this research aims to explore the relationships between deforestation and food insecurity in Madagascar using a geographic information system (GIS) to model spatial variables related to national land cover, food access, and human health.

Figure 1.1: a) Ring-tailed lemur in Southern Madagascar; b) Clear-cutting in the central highland area (photo by author, 2003)

Food insecurity is a growing concern that is linked to and embedded in other major national issues—political, natural, economic, and social (USAID, 2008). As part of the United Nations Millennium Development Goals (End Poverty and Hunger), food insecurity has been studied in detail on a global scale; however, the reported causes of the problem vary depending on the specific organization studying it, the study area, and the funding source (United Nations Development Program, 2008). Fundamentally, Madagascar's food insecurity is related to its ever increasing population, environmental degradation, and political uncertainties. Designated a "low-income food deficit nation" by the United Nations Development Program's (UNDP) Human Development Report, Madagascar ranks 143 of 177 countries on a scale of food security, similar to Ghana and Kenya (United Nations Development Program, 2008). The primary foods of the Malagasy diet are rice, cassava, and other roots and tubers (Dostie *et al.*, 2002) (Figure 1.2). Eighty-five percent of the population in Madagascar live in rural areas and therefore rely on the ability to grow their own food (WFP Madagascar, 2006).

Figure 1.2: Cassava root (http://blog.alpineinitiatives.org/2009/07/cassava-hunting.html)

In addition to food insecurity, another problem in Madagascar is deforestation. Madagascar has 250,000 plant and animal species of which 70 percent are found nowhere else on the globe, yet over 80 percent of its primary vegetation has been destroyed (Butler, 2008). Deforestation in Madagascar occurs through human activities such as clear-cutting, burning, farming, logging, and urban sprawl (Bakoariniaina *et al.*, 2006). However, the major threats to the remaining forests are driven by subsistence needs and cutting for fuel (Green and Sussman, 1990). The link between deforestation and food insecurity is entwined with economic concerns, as the forests are cut down to satisfy subsistence or financial needs. Deforestation and food insecurity are part of a positive feedback cycle, although the degree to which one affects the other is unknown. The GIS analysis will focus on this relationship and investigate the spatial variations of environmental factors influencing food access, availability, and utilization.

Research Objectives

The relationship between Malagasy deforestation and food insecurity begins with the indigenous population cutting down trees to grow cash crops, through which households obtain more money to purchase food. As time passes, however, the soil erodes and becomes less productive, which causes these households to become more food insecure. Therefore, the research question states: Is the distribution of deforestation and social factors spatially correlated with food insecurity? To answer this question, there are three main objectives.

1. Food Insecurity: Using the United States Agency for International Development (USAID) framework as a guide, develop a Food Insecurity Index (FII) that displays the most food insecure districts within Madagascar. Although USAID has assessed food insecurity in Madagascar, additional environmental and sociological variables will be used to enhance this FII.

2. Deforestation: Assess the current status of and trends in Madagascar deforestation to determine spatial variability and integrity of forest cover and soil condition.
3. Model: Using various geospatial techniques, develop a model to analyze the direct and indirect relationships among environmental and social factors influencing food insecurity.

Study Area

Madagascar is an island that has been evolving since the Malagasy tectonic plate broke away from India 70 million years ago (Rakotosamimanana, 2003). It is the world's fourth largest island, roughly the size of France, and is located in the Indian Ocean off the southeastern coast of South Africa (Figure 1.3). Madagascar is approximately twice as long (1,500 km) as it is wide (700 km), and its landscape can be divided into three parallel, long-axis, north-south zones. The eastern zone is a narrow tropical coastal plain; the central zone is a high plateau; and the western zone is a low plateau and plains (WFP Madagascar, 2006). Overall, Madagascar's rainy period is from November to March. However, there is great variation as the south is dry with an average of 300 mm of rain annually, and sections of the eastern coast receive more than 3600 mm of rain. This climatic variation influences food production. For example, the southern areas deal with severe drought, while the eastern coastal regions simultaneously experience cyclones and flooding (WFP Madagascar, 2006).

Although the island's first date of habitation is not known, it is generally accepted that the first Malay seafarers arrived about 2,000 years ago. Originally populated by 36 tribal groups, Madagascar was colonized by France in 1895 and gained its independence in 1960 after a period of provisional government (Thompson and Adloff, 1965). The transitional government and political instability further intensified problems such as poverty and deforestation (Wright, 2007). The current population is predominately a mixture of Asian and African origin.

Administratively Madagascar is divided into six provinces, 22 administrative regions, and 111 districts.

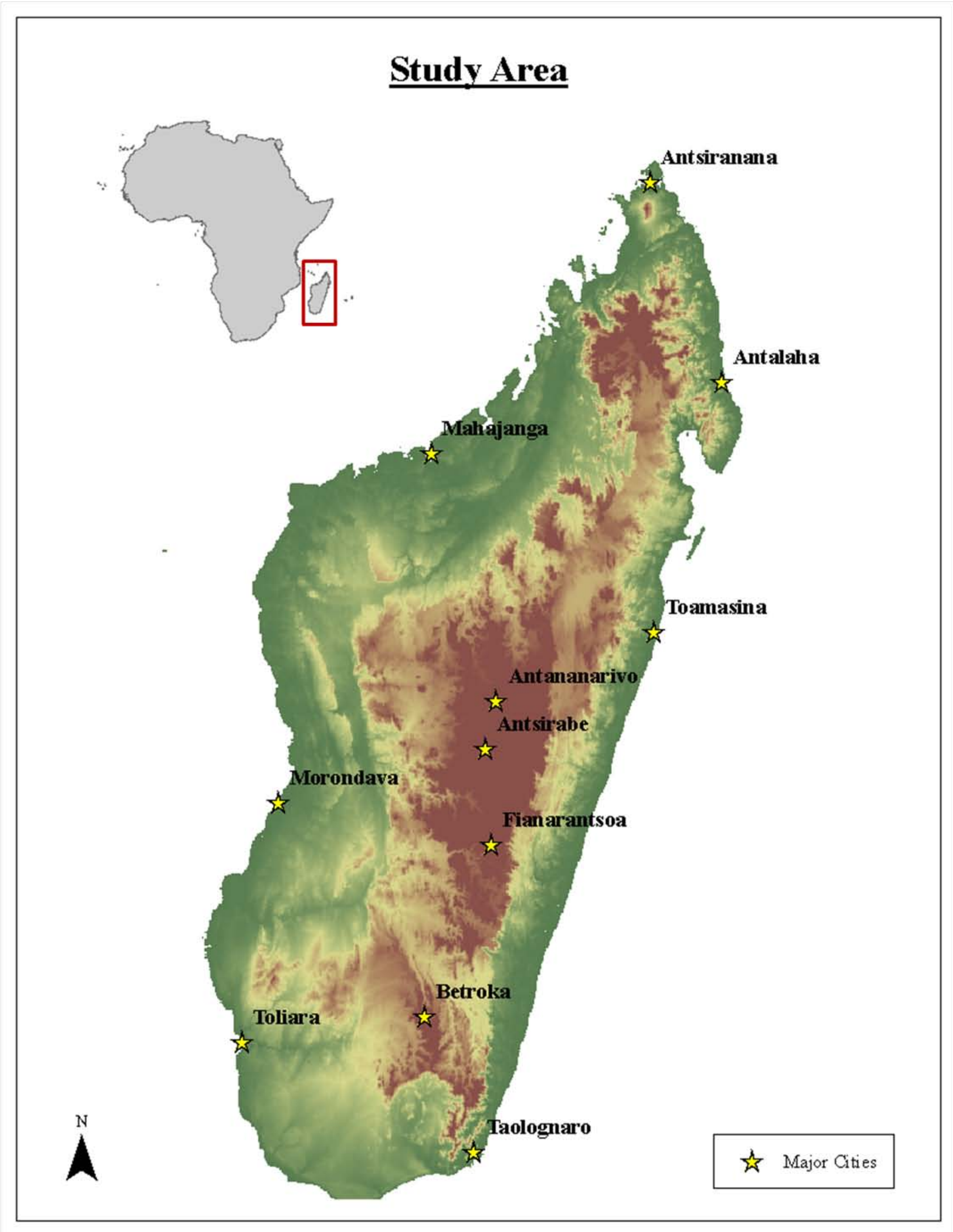


Figure 1.3: Map of Madagascar

The following chapter is a review of the concepts and literature relevant to this research, including food insecurity, deforestation, and spatial modeling. Chapter 3 is a description of the geospatial data sources and methods used in this model. Chapter 4 discusses the modeling analysis. Chapter 5 presents a discussion of modeling components and results, and Chapter 6 reviews the conclusions on the relationship between deforestation and food insecurity, as well as suggesting future research directed toward improved food security within Madagascar.

CHAPTER 2

REVIEW OF CONCEPTS AND LITERATURE

This chapter provides an overview of the literature and key concepts that are fundamental to this research. The discussion covers: 1) global food insecurity as well as the major trends in food insecurity literature; 2) deforestation in Madagascar and how it is remotely sensed and mapped globally; and 3) spatial modeling and its applications as related to food issues.

Food Insecurity

Food insecurity is a pervasive problem, with over 850 million people worldwide suffering from being chronically hungry (OneWorld, 2005). While it is clearly a global issue, the definition of food insecurity has great variation, depending on the defining organization, the location being examined, and the purpose of the study. For this project, the definition used will be from USAID in Madagascar: "Food security exists when all people at all times have both physical and economic access to sufficient food to meet their dietary needs for a productive and healthy life" (USAID, 2008). Three main aspects of this definition are important to achieving food security: availability, access, and utilization (USAID, 2008). Availability is the presence of enough food within domestic boundaries to enable the population to meet basic nutritional and caloric requirements. Some factors that affect availability at a regional level include road infrastructure, food supply, and national productivity.

Madagascar has a large food production deficit. It thus requires imports at global food prices, which directly impact food access to the majority of the Malagasy population, who live below the poverty level (WFP Madagascar, 2006). As in many parts of the world, the people primarily affected by food insecurity are the rural poor, who are most influenced by seasonal poverty (Dostie *et al.*, 2002). Access is determined by the resources a household has at its disposal to obtain food, either monetary income or its own production, which is why the spatial distribution of poverty often is similar to the spatial distribution of food insecurity. Although rice accounts for the majority of the agricultural activity and the caloric intake in Madagascar, farmers do not produce enough to feed their families. In some cases, farmers are forced to sell some rice for cash and struggle before and after harvest times (Minten and Zeller, 2000).

The last aspect of food insecurity is utilization, or the biological use of food. This includes: 1) a diet with sufficient calories and nutrients, potable water, and adequate sanitation; and 2) knowledge of food storage, basic nutrition, and child care. Some other elements of utilization include cultural beliefs regarding food and reproductive health and family planning. Utilization is typically quantified by measuring the nutritional status of children under five, and underutilization (poor nutrition) is indicated by stunting: that is, a low height-to-age ratio. This index is an indication of prolonged growth failure. Poor nutrition or food utilization slows fetus and child growth and is manifested in a failure to achieve expected height as compared to a healthy, well-nourished child of the same age (USAID, 2008).

The majority of literature concerning food security focuses on other areas of the world, such as China and India (Roy, 2003; Von Braun, 1995). Although the basic problem is the same as in those countries, Madagascar has unique problems due to its location, as well as its history and culture. The majority of Madagascar-specific food insecurity literature is produced by nongovernmental organizations (NGOs), such as USAID, United Nations World Food Programme (WFP), UNDP, United Nations Children's Fund (UNICEF), and the World Health Organization (WHO) (UNICEF, 2008; UNDP, 2008; USAID, 2008; WFP Madagascar, 2006;

WHO, 2008). These organizations gather and compile the food insecurity data and provide funding for national and local food programs.

Regardless of the study source, the existing literature reflects consistent themes concerning food insecurity. The first is the connection between poverty and food. A healthy, well-nourished person can work more, earn more, invest and consume more, and save more, ensuring future nourishment and work capacity (Bergeron, 2002). The second is that programs addressing food insecurity should focus on women and children through both education and aid. The nutritional status of an individual is primarily determined during the first years of life, when the most critical periods of growth take place; most of the functional impairments resulting from malnutrition are inflicted before two years of age (USAID, 2008). Once beyond that age, the capacity of a child to move out of poverty, and subsequently food insecurity, is greatly reduced. The third theme is that disasters or "shocks" place more of the population at risk of becoming food insecure. The WFP classifies shocks as natural (cyclones, droughts, locust infestations), social (expenses due to new school year, fees for social services), economic (global commodity prices), and political changes (uncertainty, land use regulations) that the community is unable to handle (WFP Madagascar, 2006). Numerous organizations only reference natural disasters (droughts, floods, cyclones, pest infestations), which are easier to quantify. However, the results of other disasters may be equally important yet much more difficult to quantify. For example, how will the military coup in the capital, Antananarivo, impact the food insecurity in rural Madagascar?

Deforestation

Madagascar, once known as the green island, is now called the fire island because the soil exposed during clear-cutting has colored the ground and the rivers red (Bakoariniaina *et al.*, 2006). The first modern land use projects in Madagascar were established by the French in the nineteenth and twentieth centuries as they introduced the cash crops coffee, vanilla, sugarcane, and sisal, which are still the primary exports (CIA World Factbook, 2008). As the need for food and fuel grew, cultivators cleared forested slopes for subsistence farming and charcoal production. These exposed slopes added to the degradation of the landscape due to erosion, followed by siltation of streams and rivers, and ultimately a loss of Madagascar's biodiversity (Bakoariniaina *et al.*, 2006). The deforestation started in the early 1900s in the low elevations and the flat eastern coastal region. Between 1950 and 1973, the rainforest was cleared at a rate of 51,000 ha (2.5 percent) per year. However, between 1974 and 1985, as the land became more difficult to clear and use, the rate slowed to 16,000 ha (0.79 percent) annually. This notable decrease is attributed to the lack of remaining forests on all but the steepest areas of the eastern coastal region (Green and Sussman, 1990).

Another factor in temporal changes in Madagascar deforestation involved political trends in preservation policy. Before independence from France was granted in 1960, the forests were guarded by armed members of the Department of Water and Forests. Post-1960, deforestation increased dramatically as a result of an increase in the population and a decrease in government regulation (Wright, 2007). Because Madagascar was well-known for its immense biodiversity, deforestation garnered international attention. Both NGOs and the Malagasy government invest financial support for ecosystem preservation. Establishment of nature preserves helped alleviate deforestation but did not guarantee protection (Green and Sussman, 1990). In order for preserves to be effective, local population support and cooperation is vital. Deforestation occurs for socioeconomic reasons, and therefore it is a critical issue for the island as residents debate the merits and economics of forest preservation (Bakoariniaina *et al.*, 2006).

Determining the degree of deforestation as a spatial problem can be addressed with remote sensing, a useful tool to provide broad-scale information for policy formulation and related decision making (Lucas *et al*., 2004). Many satellite sensors have been used since the 1970s to monitor global natural resources, such as the National Oceanographic and Atmospheric Administration's (NOAA) 1 km resolution Advanced Very High Resolution Radiometer (AVHRR) and the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM), with spatial resolutions of 80 m and 30 m respectively (Lillesand *et al*., 2008). The NOAA and Landsat satellite sensors are most notable, as they were able to record the dramatic changes in global forest cover in the past 50 years (Lucas *et al*., 2004). Deforestation studies have been conducted extensively in tropical areas such as Brazil and Indonesia, as well as Madagascar. A 1993 study by Skole and Tucker, for example, used Landsat satellite image data dating back to 1978 to examine tropical deforestation and habitat fragmentation within the Amazon (Giles and Burgoyne, 2008).

Most remote sensing deforestation studies use different dates of Landsat images and then conduct a post classification change detection analysis to document deforestation (Harper *et al*., 2007; Lillesand *et al*., 2008; Lucas *et al*., 2004). The quality of the land cover change detection is thus dependent upon the accuracy of the individual classification. Ideally, in order to determine quality of the classification, ground truth data should be obtained. However, gathering such data in remote areas can be expensive and time consuming. Therefore in practice, the "ground truth" is often obtained from larger-scale imagery, such as aerial photographs, without field visits (Paine and Kiser, 2003). Fortunately, general land cover classification of major categories such as forest and non-forest (i.e., cleared areas) is readily evident on medium-scale resolution satellite imagery from sources such as Landsat. Trends in Madagascar deforestation were documented in 1990 by Green and Sussman and revised in 2007 by Harper et al.

Although there might be an apparent and logical connection between deforestation and food security—people cut down the forest to grow food for a "quick fix," and then as the soil quality degrades the households become more food insecure—there has been little published on the topic. There is virtually no significant literature pertaining specifically to Madagascar or to utilizing a spatial lens to assess food insecurity. The majority of the current work has focused on India and has linked environmental quality to political conflict, which often undercuts economic potential and human well-being. In India, studies have found that the population's primary concerns are land degradation, deforestation, and contamination of groundwater due to fertilizer (Vasudeva, 2003). These environmental impacts, in turn, affect the utilization and management of natural resources and could have an adverse impact on agricultural productivity. The clearing of land for farming and the subsequent depletion of soil nutrients create a cumulative effect that will lead to the loss of land resources, environmental damage, and ultimately increased poverty and hunger (Roy, 2003).

In Madagascar, the connection between deforestation and environmental degradation has been established, although not spatially represented. The most notable deforestation studies were published by Green and Sussman in 1990 and most recently in 2007 by Harper et al. for Conservation International (CI). The Green and Sussman (1990) study used aerial photos from 1950 and Landsat images from 1972 to 1973 and 1984 to 1985 to calculate the rate of deforestation of the eastern tropical rainforest over the 35-year period (Green and Sussman, 1990). The Harper et al. report utilizes aerial photos from circa 1953 and Landsat images from as recently as 2000 in order to conduct a change analysis. The final product is estimated to have

89.5 percent accuracy in identification of forest/non-forest (Harper *et al.*, 2007). In 1993 Nelson and Horning published an alternative method for delineating forest/non-forest areas within Madagascar. Using the Advanced Very High Resolution Radiometer-Local Area Coverage (AVHRR-LAC) sensors, a forest/non-forest map of the entire island was created. Change analysis was conducted with older Landsat data to determine the overall forest area lost from the 1970s to 1990. The AVHRR-LAC map class agreement was 78.2 percent, with a map accuracy of 81.1 percent (Nelson and Horning, 1993). In summary, few deforestation projects focus on the entire nation of Madagascar, and none have been conducted at a scale that spatially connects the physical process of deforestation with the human issue of food insecurity.

Spatial Modeling

Models are simplifications used to represent reality. Computer-based spatial models using GIS describe, explain, or predict forms and practices and are often called cartographic models (Bolstad, 2008; Longley *et al.*, 2009; Tomlin, 1990). Through the integration of geospatial layers or variables, GIS modeling encompasses the varied applications of the concepts, procedures, and approaches inherent in spatial analysis. Spatial models primarily fall within the three dominant GIS modeling frameworks, with their main purposes being suitability, decision support, and statistical modeling (Berry, 2009). Within each conceptual framework, GIS models can be further divided into two main categories—spatiotemporal and cartographic models. Spatiotemporal models are dynamic in both space and time, whereas cartographic models involve specific points in time. These cartographic models analyze multiple data layers in a static representation of the variable values at a specific time as they relate to the study area (Bolstad, 2008). The layers are typically contained within a GIS database, enabling all layers to be registered to the same ground coordinate system (Tomlin, 1990). A cartographic model typically contains numerous layers, such as topography, climate, soil type, or any social factors that are linked to a geographic area. Cartographic modeling provides information and analysis through a combination of spatial data sets, functions, and operations usually combined via operations or map algebra (Bolstad, 2008).

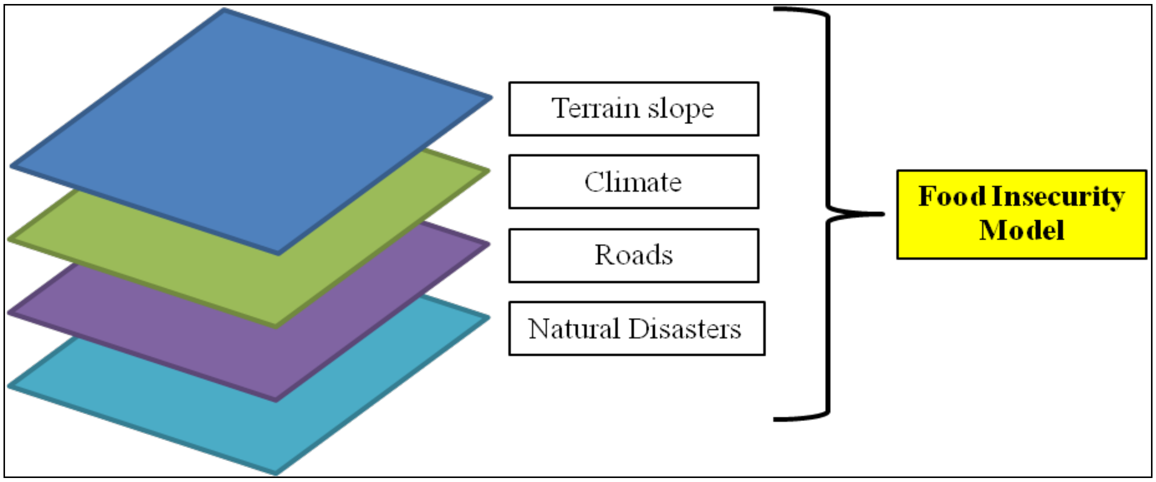


Figure 2.1: Example GIS database containing some factors related to food insecurity

Three elements are essential to GIS—data, operations, and applications. The GIS software does not provide the spatial model to the user independently. The user must determine what data or variables to use as input and which operations are suitable for the model (Tomlin, 1990). Spatial modeling is used in a wide variety of research, from ecological endangered species preservation to transportation route optimization. One area in which GIS modeling is used extensively is land use and resource management (Chomitz and Gray, 1996; Mertens and Lambin, 1997).

Chomitz and Gray (1996) used GIS modeling and different layers of data to analyze how the creation of a road can influence land use and deforestation in Belize. The data layers included SPOT satellite derived land use, slope, rainfall, and other environmental factors. This study also included roads as a social or human influence. The Mertens and Lambin (1997) study identified the areas with the greatest propensity for deforestation within Cameroon. Again, the only social variable considered in the study was the distance to roads. Although these studies were able to answer the research questions posed, GIS models can incorporate more social variables to create a better representation of complex problems.

Spatial modeling is primarily used for modeling natural resources and less for social models. However, it is becoming more common to use participatory mapping in conjunction with GIS to model the interactions between humans and the environment (Bohra and Andrianasolo, 2001; Robiglio *et al.*, 2003). Robiglio et al. (2003) studied the social arrangements that influence the land use in Cameroon. This study used local knowledge about the area and used the participatory component of the research to ascertain why the spatial land use patterns existed (Robiglio *et al.*, 2003). The Bohra and Andrianasolo (2001) study was focused in India and used both environmental and sociocultural data to produce a dengue risk assessment. Their data collected through interviews was combined with other spatial data (climate, land use, crime rates). The study's results could then be used to implement preventive strategies.

GIScience spans the natural-social divide and allows study between these two realms (Longley *et al.*, 2009). Within Madagascar many studies have focused on endangered species or deforestation; however, there is little study regarding the people. Research has focused on either land use as connected to deforestation or on population studies that did not use spatial analysis (Agarwal *et al.*, 2005; UNICEF, 2008). When analyzing the complex issue of food insecurity, it is important to consider both environmental and social factors. This research will create a decision support model that is unique in spatially assessing both environmental and social features/layers related to availability, access, and utilization of food as an index of food insecurity. As Chapter 3 outlines, the spatial model implemented in this thesis involves GIS operations such as surface interpolations, reclassifications, buffer/distance analysis, and map algebra, while including social variables as well as physical and environmental factors.

CHAPTER 3

METHODOLOGY FOR FOOD INSECURITY MODELING

Spatial Data Sources

This chapter provides a description of the spatial data sets used in this research. There will also be a detailed description of the methods used in the creation of the Madagascar Food Insecurity Index (FII). In order to investigate the relationship between social factors, deforestation, and environmental properties as they relate to food insecurity in Madagascar, a search was conducted to locate existing spatial data sets documenting these inputs. Details on the data sources are described below.

Social Factors

To begin examining the spatial distribution of food insecurity within Madagascar, several data sets were consulted. The USAID FII data were taken from its September 2008 Madagascar Food Security Programming Framework. The source of data for the additional availability, access, and utilization variables was the 2001 Madagascar Census, organized by the Ilo program of Cornell University at the end of 2001. Although a 2007 census was conducted through the Ilo program, an April 2008 military coup prevented the data from being released. Since the data are the property of the Malagasy government, the 2007 census data set is not available for use in this study (Moser, personnal communication, March 30, 2009). For the Madagascar FII, the census data set is classified as social factors, as this data is derived from the 2001 census questionnaire.

The data for social factors of food insecurity in Madagascar are inconsistent at best. Although national-level information from a government-funded organization would have been preferred, it is unavailable for this study. When examining older data, the Madagascar National

Institute of Statistics (INSTAT) was found to have useful products, but due to current political instability in Madagascar, it could not be contacted. Food insecurity data that could be located were inconsistent since each NGO defines variables differently, reports them at a different scale, and has a specific agenda. These differences yield great variation in the final output, resulting in very different representations of the distribution of food insecurity (Figure 3.1). The USAID data were collected as a household survey and then aggregated to the district level (Figure 3.1a). For other NGOs, data were collected and then aggregated to the province level; there are six provinces (Figure 3.1b).

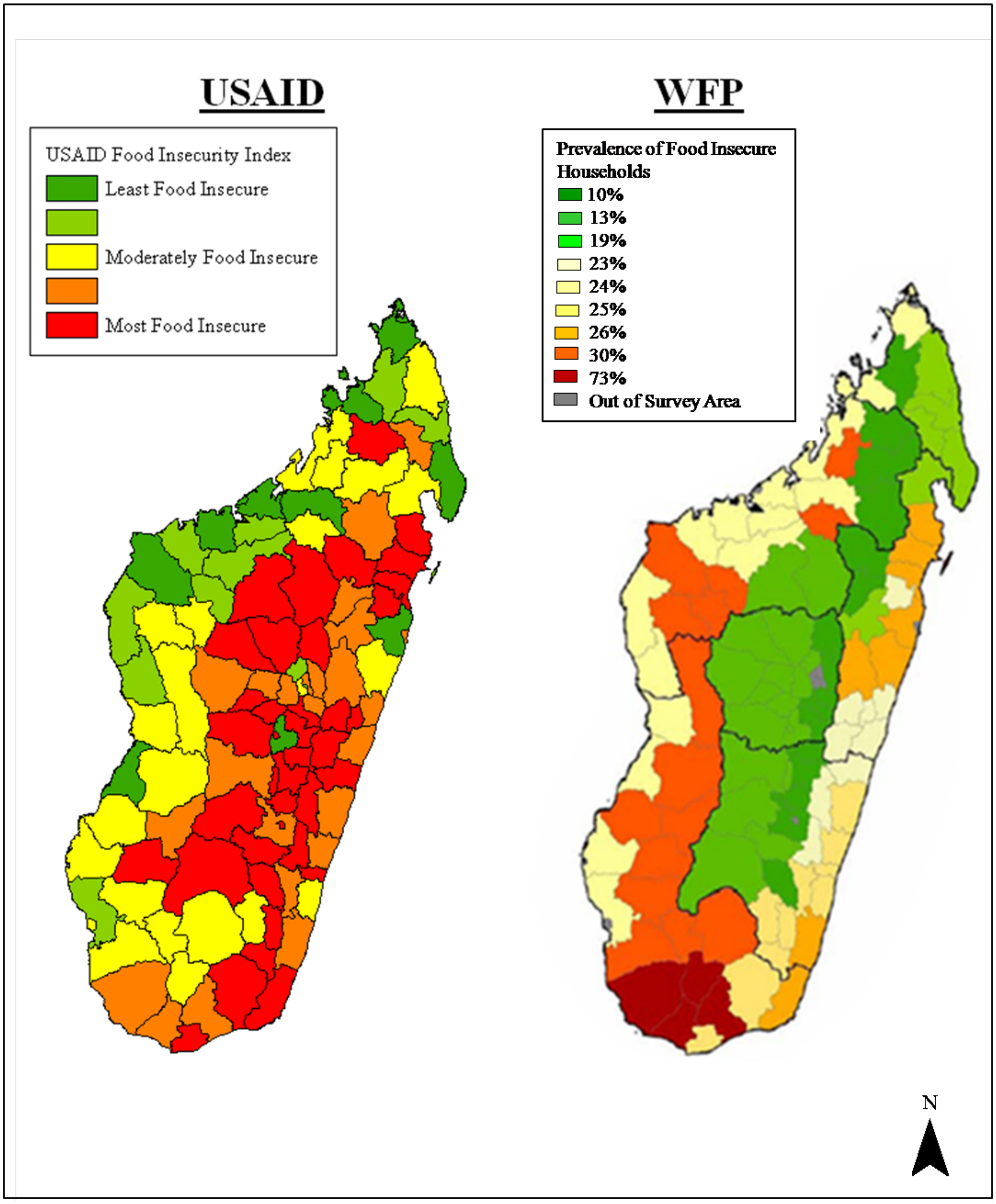


Figure 3.1: a) USAID Food Insecurity Map (September 2008); b) WFP Prevalence of Food Insecure Households (April 2006)

While collecting from the diverse data sets for this research, the major concern was with the various dates of the data sets, the level of aggregation, and the specific variables chosen. Differences in the dates of the 2008 USAID FII and the 2001 census information could impact the findings. The USAID FII is a composite of different collection dates ranging from 1993 to 2004, but all other data is taken from the 2001 census. The level of aggregation is also a problem. The FII is aggregated and reported at the district level (polygons), with the census data recorded as survey sites (points).

The social factors selected to represent food insecurity in this study fall within the internationally accepted USAID framework. For the model each variable will represent the factors of food availability, access, or utilization. The percentage of the population involved in the agriculture sector represents availability, because as more cash crops are produced, less land is available to grow food to consume. The cash crop farmer is also susceptible to global food price fluctuations. The percentage of household income expended for food represents access. If a household spends a large majority of their income on food, a shock or loss of income causes the household to go without food. The percentage of the population constituted by underweight mothers represents utilization. If mothers are underweight when they give birth, then there is a high probability that the child will also have low birth weight and be underdeveloped.

Shocks are an input to the Madagascar FII model in this study because they can affect infrastructure, soil properties, and food production and distribution. The shock layer is a combination of all shocks to which the population feels they are susceptible. These data were collected during the 2001 Madagascar Census and include cyclones, floods, impassable roads, droughts, plant sicknesses, locusts, and early or late rains. In the Madagascar FII model, shocks represent both access and availability, as they influence all parts of daily life.

The Malagasy transportation network is an additional variable in the FII model. Both roads and railroads represent food availability because these transportation routes are the main means of food distribution and cash crop sales to markets under normal conditions and of aid distribution during times of extreme food shortages. Road access is a major problem throughout the country, as there are about 50,000 km of roadways, of which only about 6,000 km are paved (1999 estimates) (WPF Madagascar, 2006). Although this is a small percent, the paved roads are important to consider for both food insecurity and economic development. This shapefile data set was downloaded from MapCruzin (www.mapcruzin.com), an independent firm specializing in innovative GIS projects, environmental and sociodemographic research, and website development and hosting as well as from OpenStreetMap (www.openstreetmap.org), an internet mapping site to which the global community contributes road collation and name information on a voluntary basis.

Deforestation

In addition to the social inputs, deforestation and human-influenced landscape change also affect food insecurity. Similar to previous studies of deforestation in Madagascar by Skole and Tucker (1993) and Harper et al. (2007), *forest* is defined as areas of primary vegetation dominated by tree cover at least seven meters in height with neighboring trees' crowns touching or overlapping when in full leaf. In order to delineate areas of deforestation, a time series of satellite images is required to detect change. Harper et al. (2007) used two main types of images. The first is a set of aerial photographs acquired in 1949-1957 that were scanned and orthorectified. The second set of data is Landsat images taken from NASA's Geocover project for the 1970s, circa 1990, and circa 2000. The 1990 and 2000 images were both derived from Landsat TM/ETM+ data at 30-m resolution and compared using a supervised classification.

Using the analyst-defined training set, Harper et al. (2007) classified each image into five main classes: forest, non-forest, water, cloud/shade (no data), and mangrove. The land cover change was then calculated. Each training set was determined through visual interpretation, through consultation with biologists familiar with Madagascar's landscape, and through purchased aerial photos and five days of overflights. Once the classification was complete, two filters, majority filter and "eliminate" function, were implemented during postprocessing to refine the final product. The 1970s data were classified separately due to the lower spatial resolution. The same method of classification was performed and the classification data set was then merged with the 1990-2000 images. Due to the internal geometric differences of the 1950s photo data and the satellite images, it was impractical to merge this data set. Therefore, an aggregate numerical forest change estimate was made for 1950-1970, in contrast to the spatially explicit forest change estimates for the 1970-1990 and 1990-2000 periods. An accuracy assessment of the final map was conducted during low-altitude flights in September 2002. It is estimated that this study achieved 89.5 percent accuracy in identification of forest and non-forest (Harper *et al.*, 2007).

Due to the completeness of this study, the Harper et al. (2007) forest change was used for the deforestation data in this research. Harper et al. had access to aerial photos as well as Malagasy experts advising training set delineation, both of which are unavailable at this time. The accuracy assessment of 89.5 percent is sufficient for this research. The article was published in a peer-reviewed scientific journal, *Environmental Conservation*, and Dr. Harper is well known in the field of tropical forest mapping.

The deforestation layer will serve as an input into the Madagascar FII model and will represent the changing landscape and soil productivity. Areas that have been deforested become susceptible to massive erosion and floods, while the soil nutrients are depleted due to the loss of soil and unsustainable agriculture practices (Gade, 1996). These areas will then have a limited productivity and therefore will represent diminished food availability within the Madagascar FII model.

Physical Properties

Along with deforestation, other physical or environmental properties must be included for the Madagascar FII model to represent the complexity of the problem. Data sets for the variables annual precipitation, elevation, and soil characteristics were downloaded from a variety of sources and then manipulated for input in the Madagascar FII model as follows.

The precipitation data are a set of global climate layers with a spatial resolution of 1 km^2 and the data are referred to as the "WorldClim" database (Hijmans *et al.*, 2005). This data set is a series of climate surfaces taken from five sources: Global Historical Climate Network Dataset (GHCN) version 2, World Meteorological Organization (WMO) climatological normals, FAOCLIM 2.1 global climate database (CD-ROM from the Food and Agriculture Organization of the United Nations), International Center for Tropical Agriculture (CIAT) database, and regional databases for Latin America and the Caribbean (Hijmans *et al.*, 2005).

A global digital elevation model (DEM) produced from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data is known as the Global Digital Elevation Model (GDEM). This product was created jointly by the Ministry of Economy, Trade and Industry of Japan (METI) and the National Aeronautics and Space Administration (NASA) and is available for download using the NASA Warehouse Inventory Search Tool (WIST). The GDEM has a spatial resolution of 30 × 30 km tiles (Lillesand *et al.*, 2008). In order to cover the entire island of Madagascar, 81 tiles were used. The soil characteristics are represented by the soil erodibility, commonly known as the K-factor. It represents the average long-term soil and soil-profile response to the erosive power associated with rainfall and runoff (Millward and Mersey, 1999). This data set was derived from a presentation by Honzak and Wendland (2007) from the International River Symposium proceedings. Their research objective is to use GIS in order to link the best available ecological and economic data and hydrological services in Madagascar. Figure 1 is a summary of the variables that serve as inputs in the Madagascar FII model.

Table 3.1: Summary of Variables Table

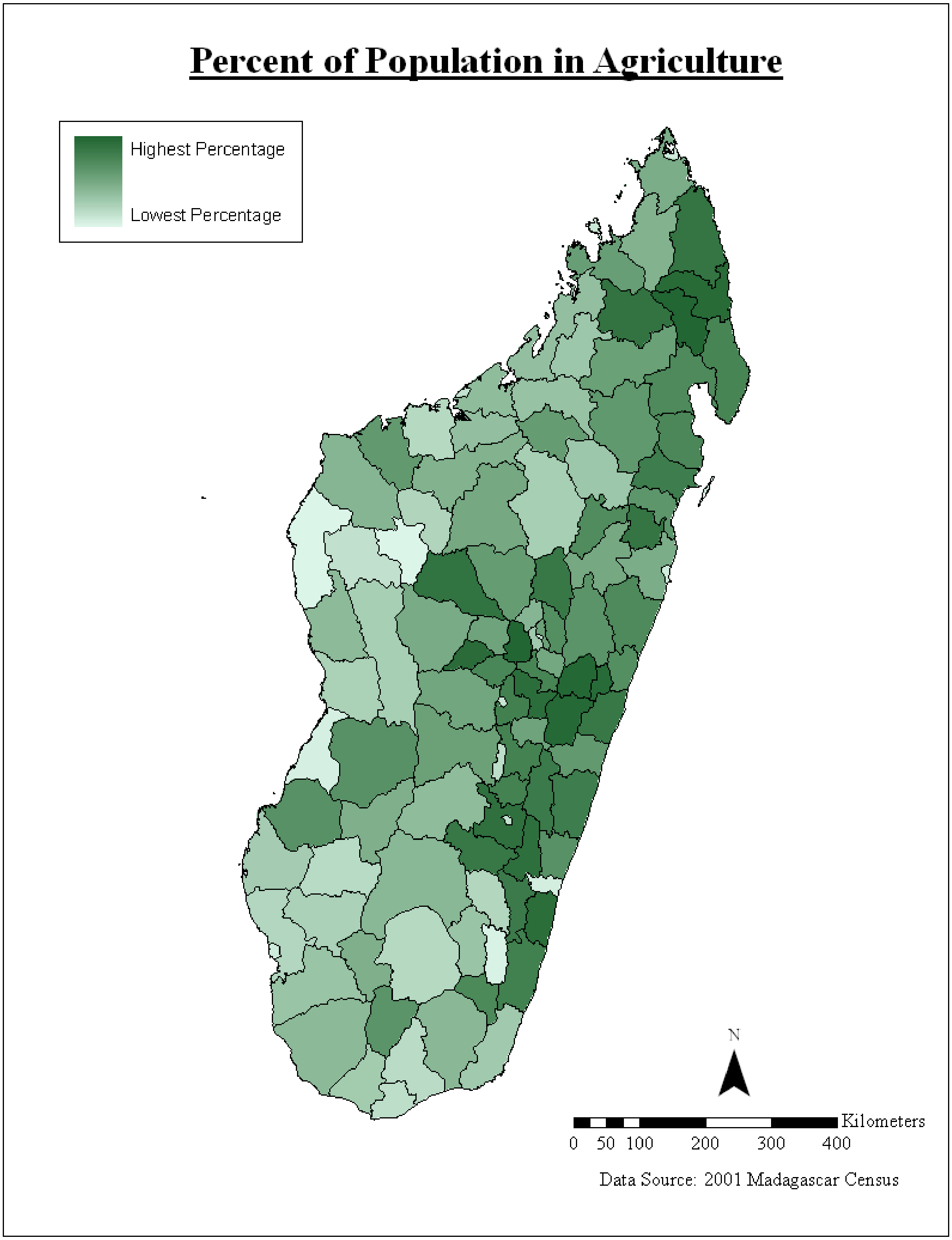
Variable	Source	Component to FII model
Percent Population in Agriculture	2001 Madagascar Census	Availability
Total Household Food Expenditures	2001 Madagascar Census	Access
Underweight Mothers	2001Madagasar Census	Utilization
Total Shocks	2001 Madagascar Census	Availability/Access
Roads	OpenStreetMap	Availability
Railroads	OpenStreetMap	
Deforestation	Harper *et al.*, 2007	Availability/Access
Average Precipitation	WorldClim database	Access
Digital Elevation Model	ASTER GDEM	
Soil Erodibility	Conservation International	

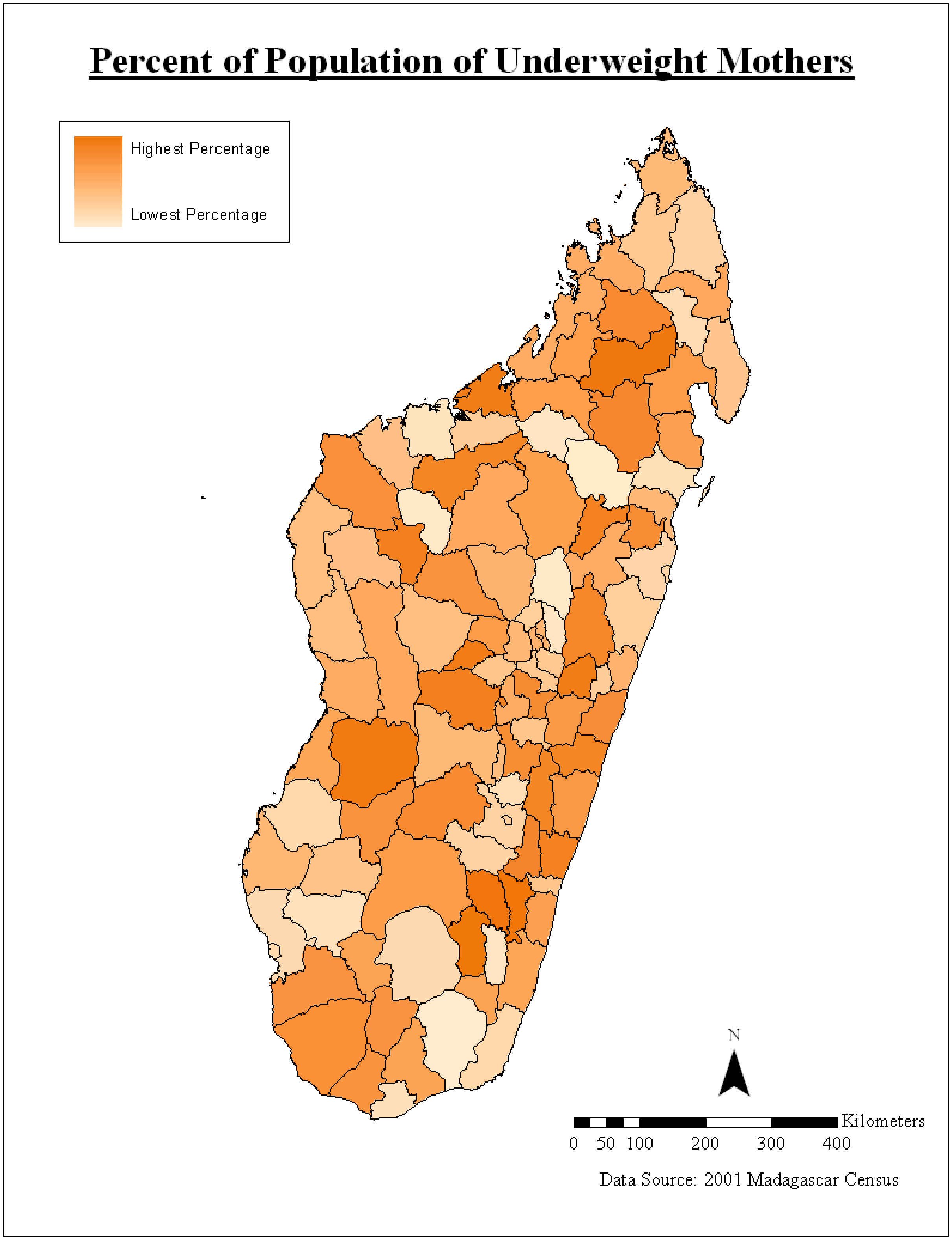
Data Analysis

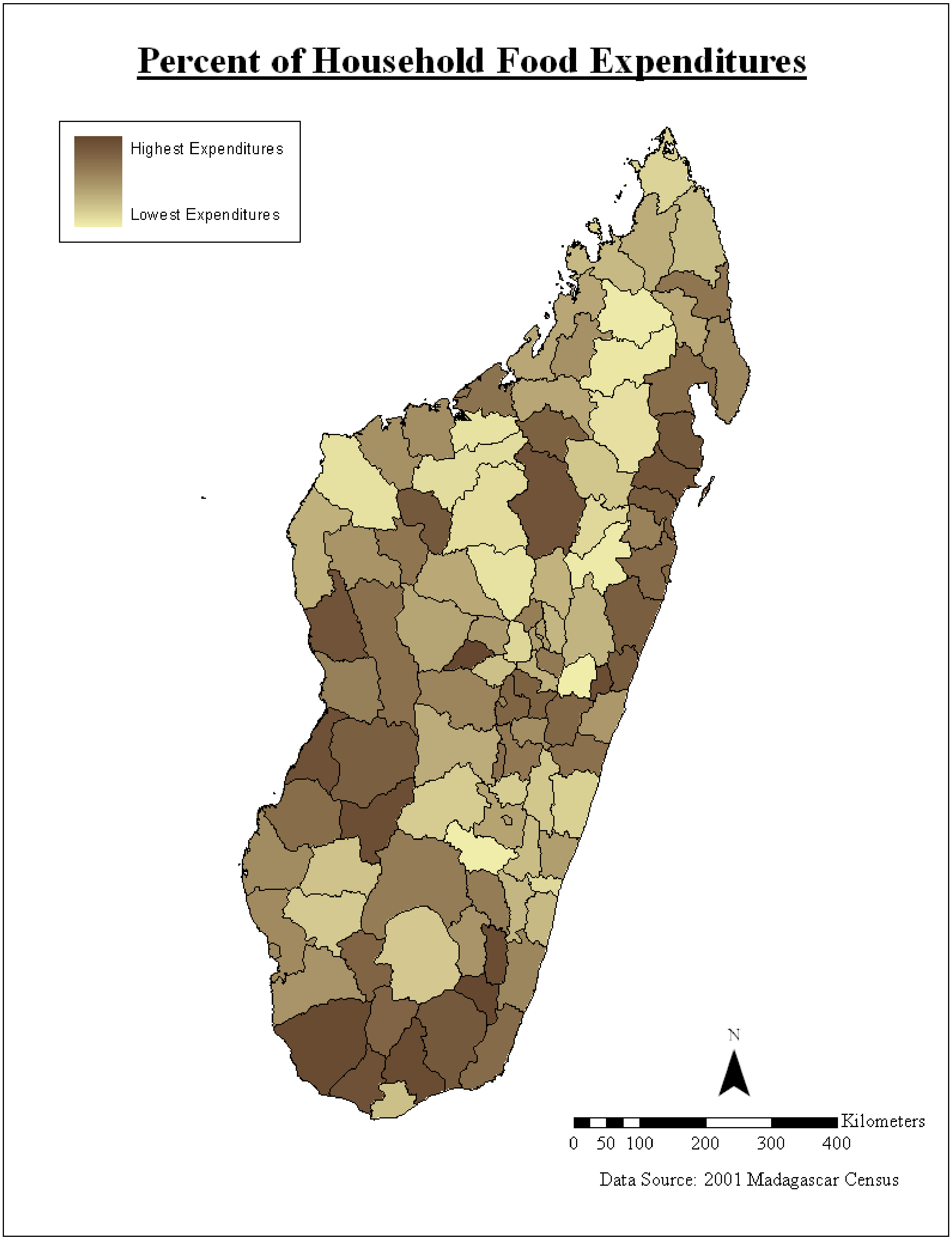
The data sources are diverse and therefore allow the Madagascar FII model to be a robust representation of the complex issue of food insecurity. By combining the social factors with land cover and physical properties, most facets of the food insecurity problem will be addressed. The data analysis section will be organized by a description of each of the three data individual segments: social factors, deforestation, and physical properties, with the last section describing the Madagascar FII model.

Social Factors

Four of the social factors were taken from the 2001 Madagascar Census and aggregated to the district level. These variables are percentage of the population in agriculture, percentage of the population constituted by underweight mothers, percentage of household income expended on food, and number of perceived shocks. The distribution of each variable can be seen in Figure 3.2.


Percent of Population in Agriculture
Highest Percentage
Lowest Percentage
N
Kilometers
0 50 100 200 300 400
Data Source: 2001 Madagascar Census


Percent of Population of Underweight Mothers
Highest Percentage
Lowest Percentage
N
Kilometers
0 50 100 200 300 400
Data Source: 2001 Madagascar Census


Percent of Household Food Expenditures
Highest Expenditures
Lowest Expenditures
N
Kilometers
0 50 100 200 300 400
Data Source: 2001 Madagascar Census

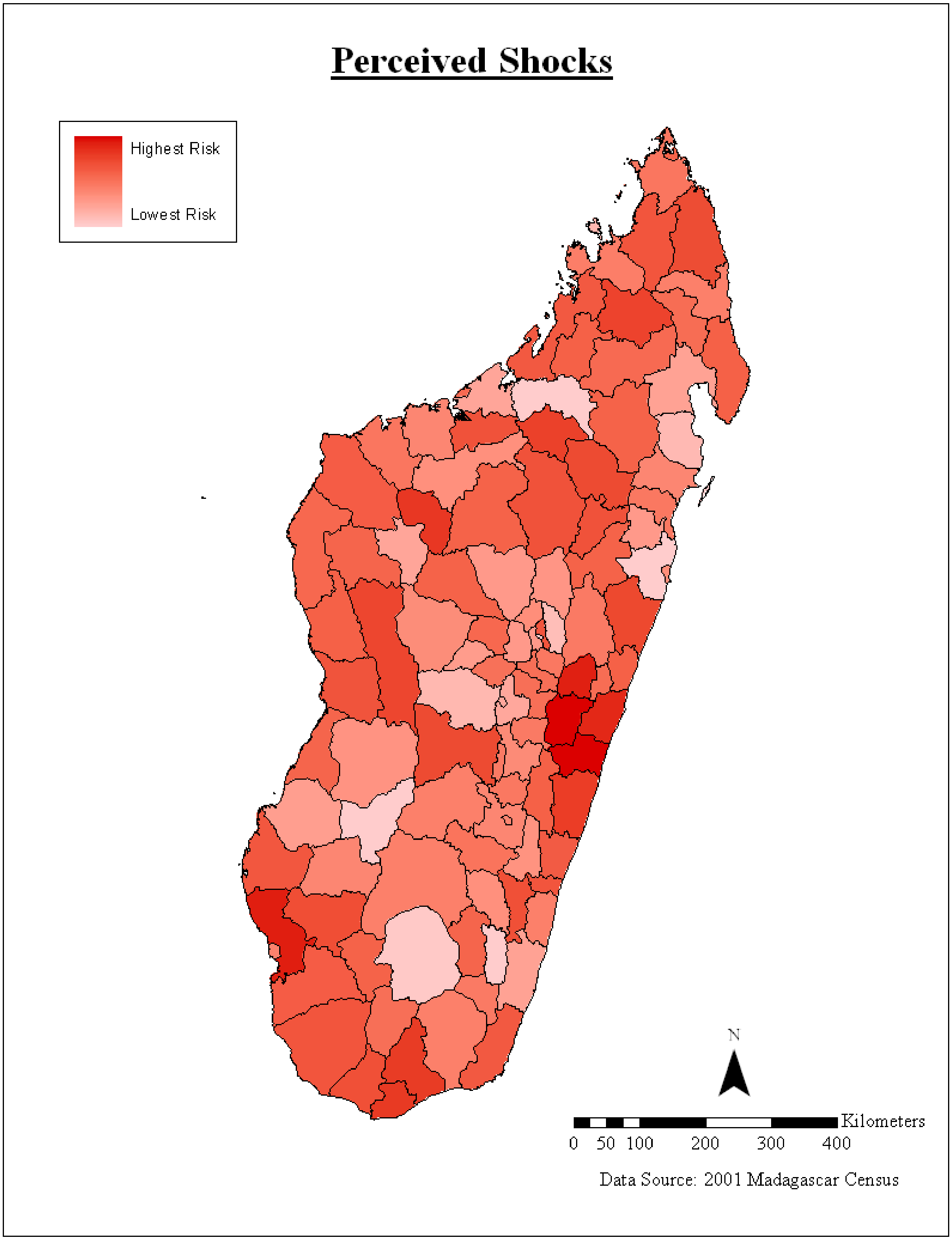


Figure 3.2: a) Percent of the population involved in agriculture; b) Percent of the population constituted by underweight mothers; c) Percent of household income expended for food; d) Number of perceived shocks

Based on initial visual analysis, the percentage of the population involved in agriculture is clustered in the eastern portion of Madagascar (Figure 3.2a). These are the areas where the most rice is grown not only for national consumption, but also for sale on the global market. The percentage of the population constituted by underweight mothers is generally moderate to high throughout Madagascar (Figure 3.2b), and the percentage of household income expended on food is generally highest in focused areas on the west, east, and southern coasts (Figure 3.2c). The perceived shocks are highest for the outer ring of districts, as those areas experience cyclones (east and west coasts) and droughts (south) (Figure 3.2d). Although these characteristic patterns are based on visual assessment, further statistical analysis as described in Chapter 4 was performed to identify clustering.

The final social factor used in the Madagascar FII model was transportation, which is a combination of both railroads and primary roads. Although labeled "primary roads," they are often still unpaved, usable only by four-wheel-drive vehicles, and often washed out by floods and other weather events (personal observation, 2003). Even where roads exist, entire regions are inaccessible during parts of the rainy season because of the poor infrastructure. In the final transportation layer, the roads and railroads were buffered on each side by 5 km to define the area for which transportation routes would affect food availability. If the road were to become impassible, it is assumed that people would be able to walk at least 5 km to obtain food and/or clean water. This layer is important to the model as it addresses the infrastructure status of Madagascar. Thus, any areas outside the transportation buffer zone of 5 km on either side of the road would have greatly decreased food availability by any aid organization. The final transportation layer, representing the distribution and walking buffer, is shown in Figure 3.4.

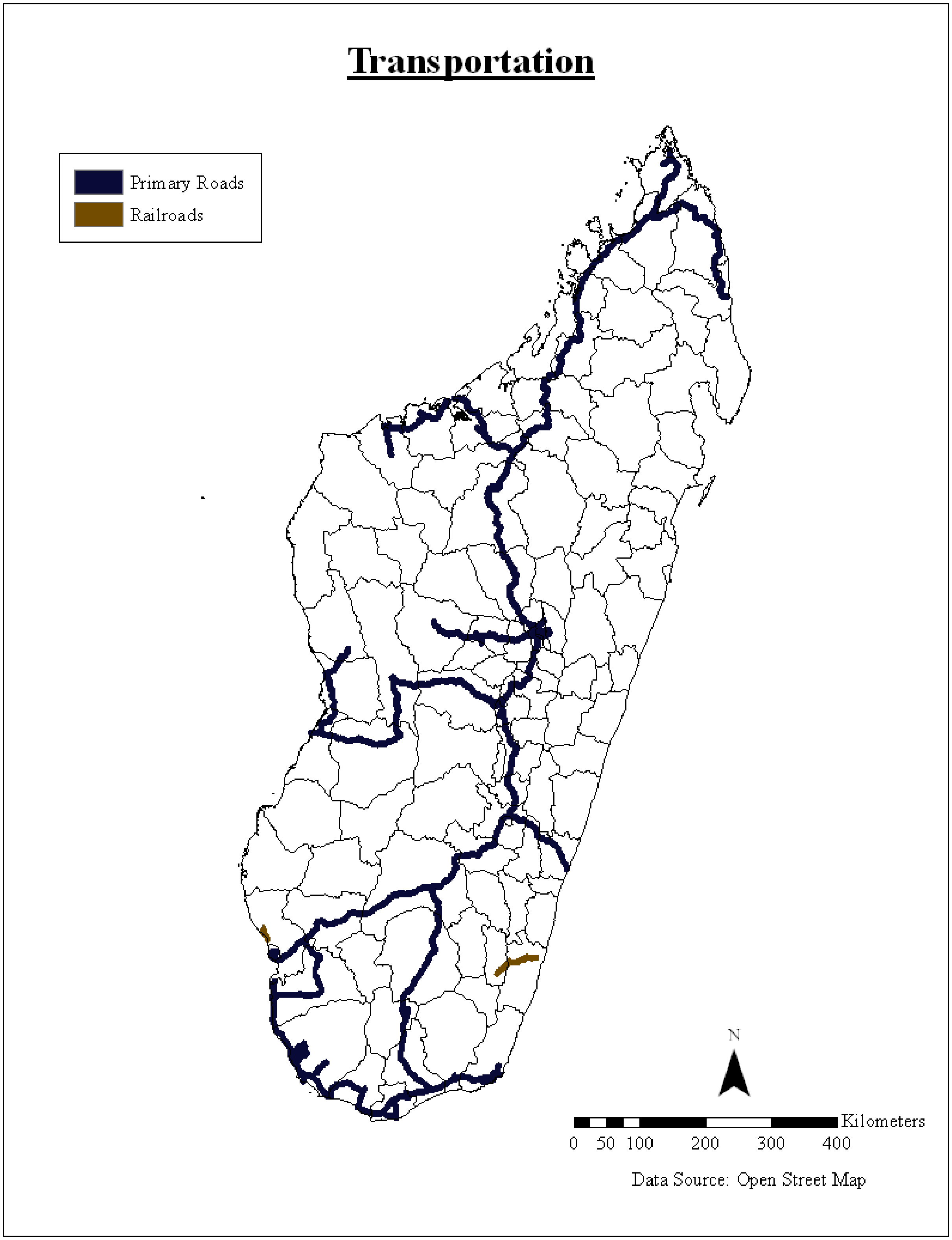


Figure 3.3: Major Transportation Routes

Deforestation

In order to create a digital map of deforestation in Madagascar, previous research and products were used, specifically the Harper et al. (2007) map created by the scientists from Conservation International (CI) (Figure 3.5). Attempts to obtain these data from the authors were not successful; therefore the image in the published article was saved as a digital file in TIFF format.

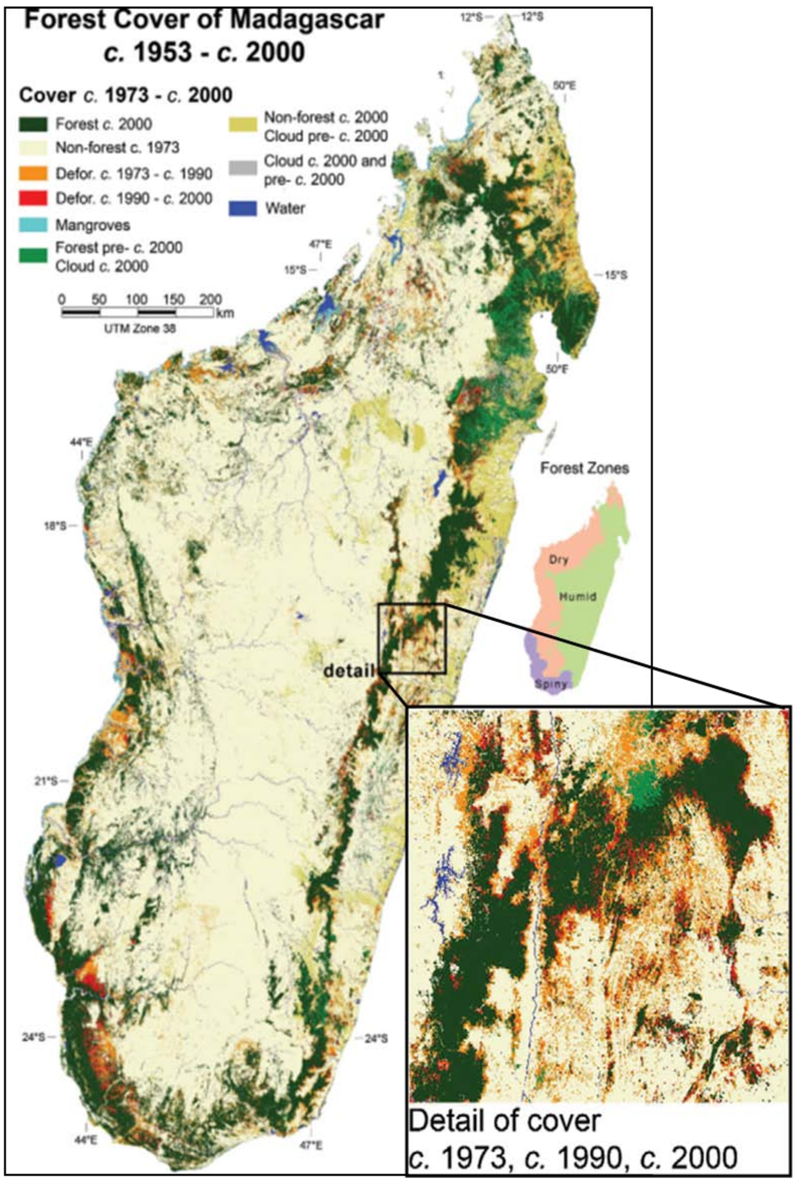


Figure 3.4: Harper et al. (2007) deforestation map

The image of Madagascar was then georectified using the Madagascar boundaries shapefile from ESRI using the World Geodetic Systems of 1984 (WGS84) datum, Universal Transverse Mercator Zone 38S ground coordinate system. Using 13 control points, the total Root Mean Square Error (RSME) was 0.03541, indicating that the first-order polynomial transformation is an adequate fit for the data. In order to transform the published image into a raster data set that could be manipulated in the Madagascar FII model, this image was then reclassified using ERDAS Imagine 9.3. Using the supervised classification method, 21 training sets were created. The classes were then collapsed into the final 5 classes: non-forest/cloud cover, forest, non-forest, deforested 1973-2000, and water. Once the classification was complete, the image still contained many single pixels and small clusters, so postprocessing was necessary. Two noise-reduction filters were used to smooth the edges and refine the final image. In order for areas to be calculated, the classified pixel clusters were converted to polygons and intersected with district boundaries. The areas of the deforested polygons were calculated and divided by the total area of each district to determine the percentage deforested, which ranged from 0 to 45 percent. From those values, the districts were ranked; the map in Figure 3.6 shows the distribution. Similar to the Harper et al. (2007) map, the periphery of the island is the most deforested.

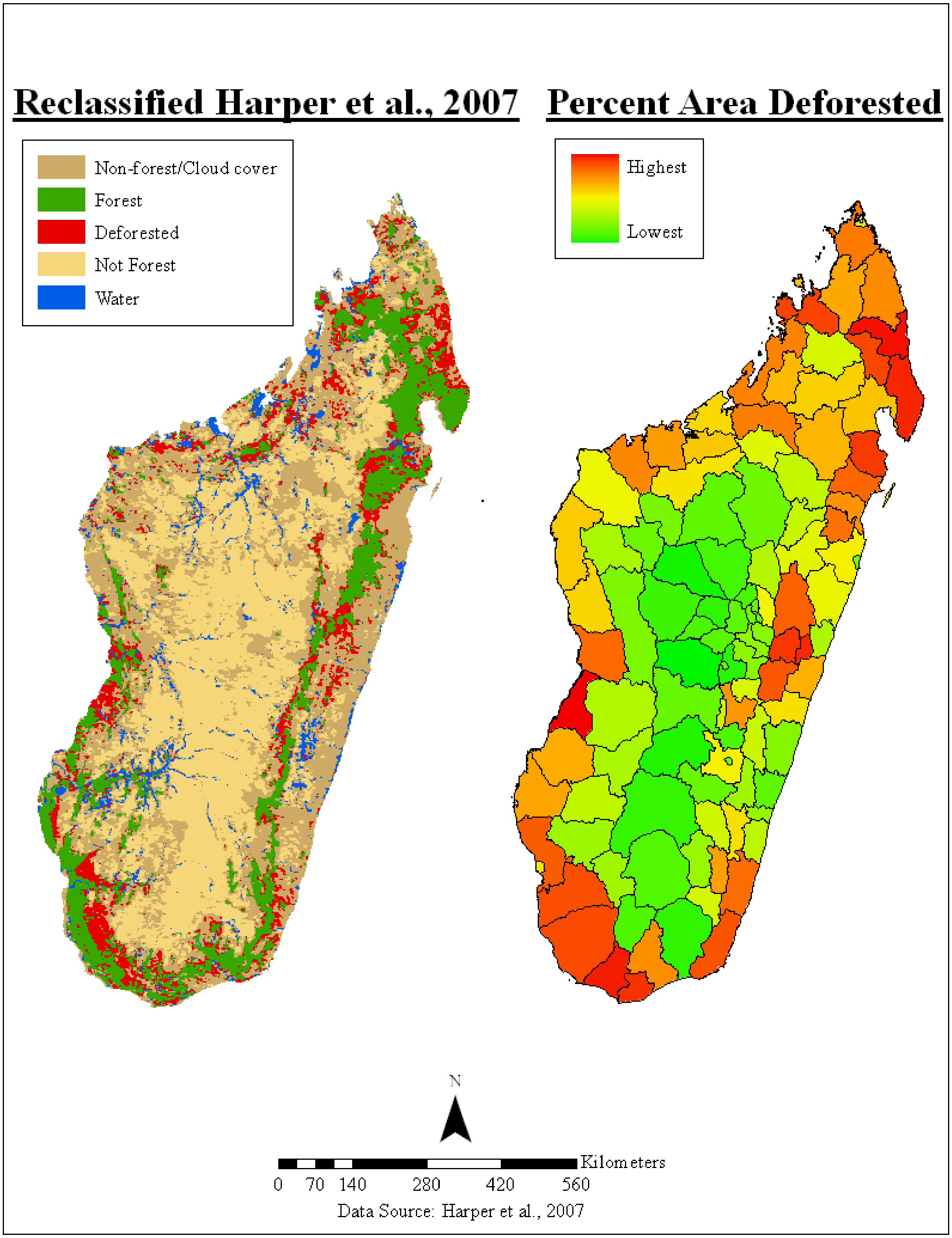


Figure 3.5: a) Reclassified Harper et al. (2007) map; b) Percent area deforested (of each district)

The districts with the highest percentage area deforested are along the outer ring of the island. This is logical, as that is where the majority of the original forest existed (the central highlands were primarily grasslands and savannah), and this is also where the climate is conducive to rice cultivation.

Physical Properties

The physical properties allowed for additional variables to be considered within the model, as there are many environmental concerns involved in food production, soil quality, and erosion. The soil erodibility data set initially was not in a usable format, and therefore the image was downloaded and georectified and the K-factor polygons were digitized. Although the polygons are much larger than the districts used for the social factors, the accuracy of the layer is sufficient for this aspect of the model. The second physical property is the average monthly precipitation. Because this is a global data set, it was clipped for Madagascar to manage the data volume and to ensure that the final Madagascar FII model will run smoothly. These final layers of soil erodibility and average monthly precipitation (mm) are shown in Figure 3.7.

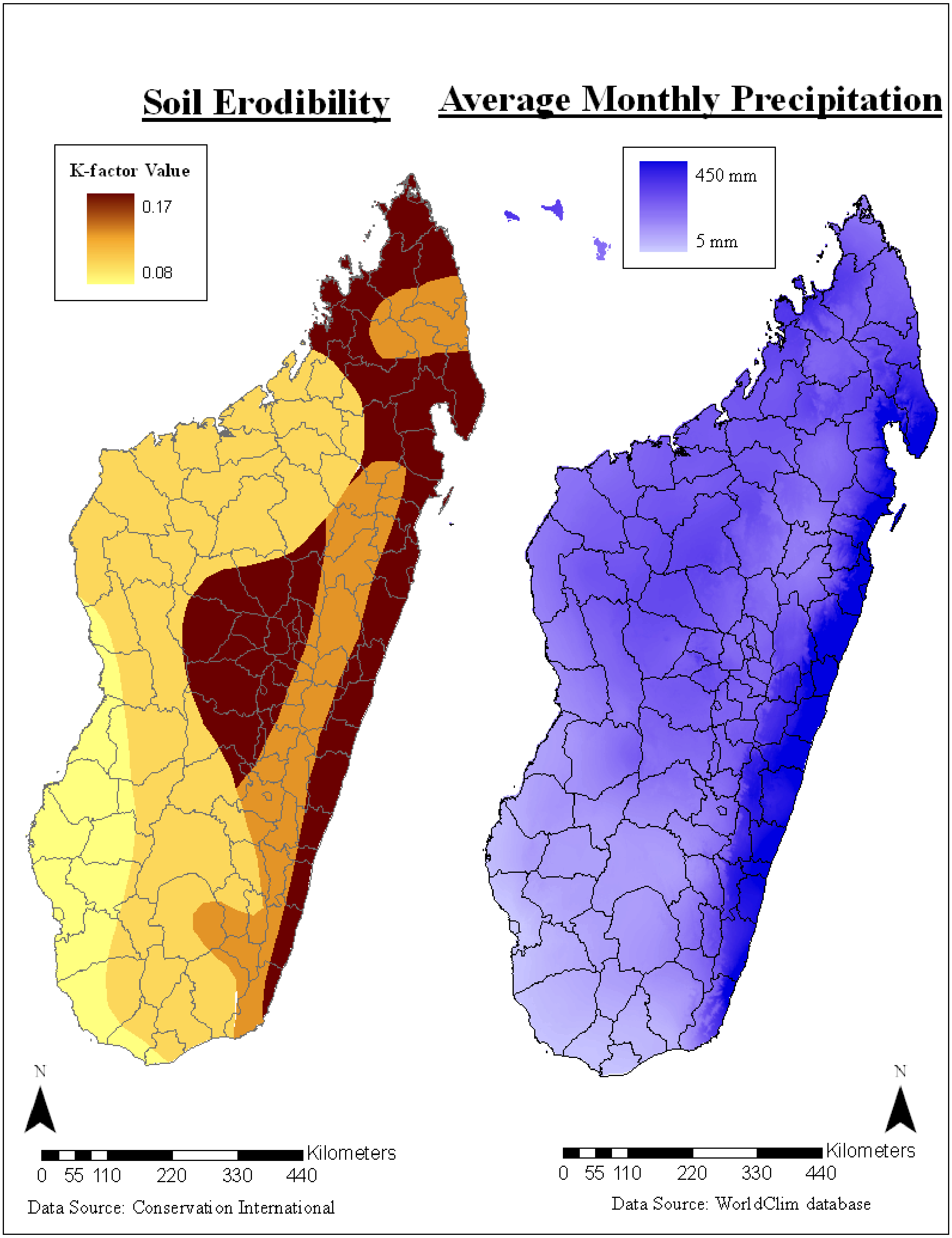


Figure 3.6: a) Soil erodibility; b) Average monthly precipitation (mm)

The last physical property relates to slope, which identifies the steepest downhill angle for each location. Slope was derived from the ASTER GDEM. The ASTER GDEM tiles were downloaded and a mosaic of the island was created. From the GDEM, the slope was derived using the ArcGIS slope function. Both elevation and slope are shown in Figure 3.8. There are areas of high slope throughout the island, but most are on the eastern half. Similar to the Everglades Landscape Model (a broad-scale model on the order of the Madagascar FII model), the slope was ascertained using 1-km^2 spatial resolution (Fitz, 2002). Because they are both regional studies, the cell size is appropriate for the necessary detail and model efficiency.

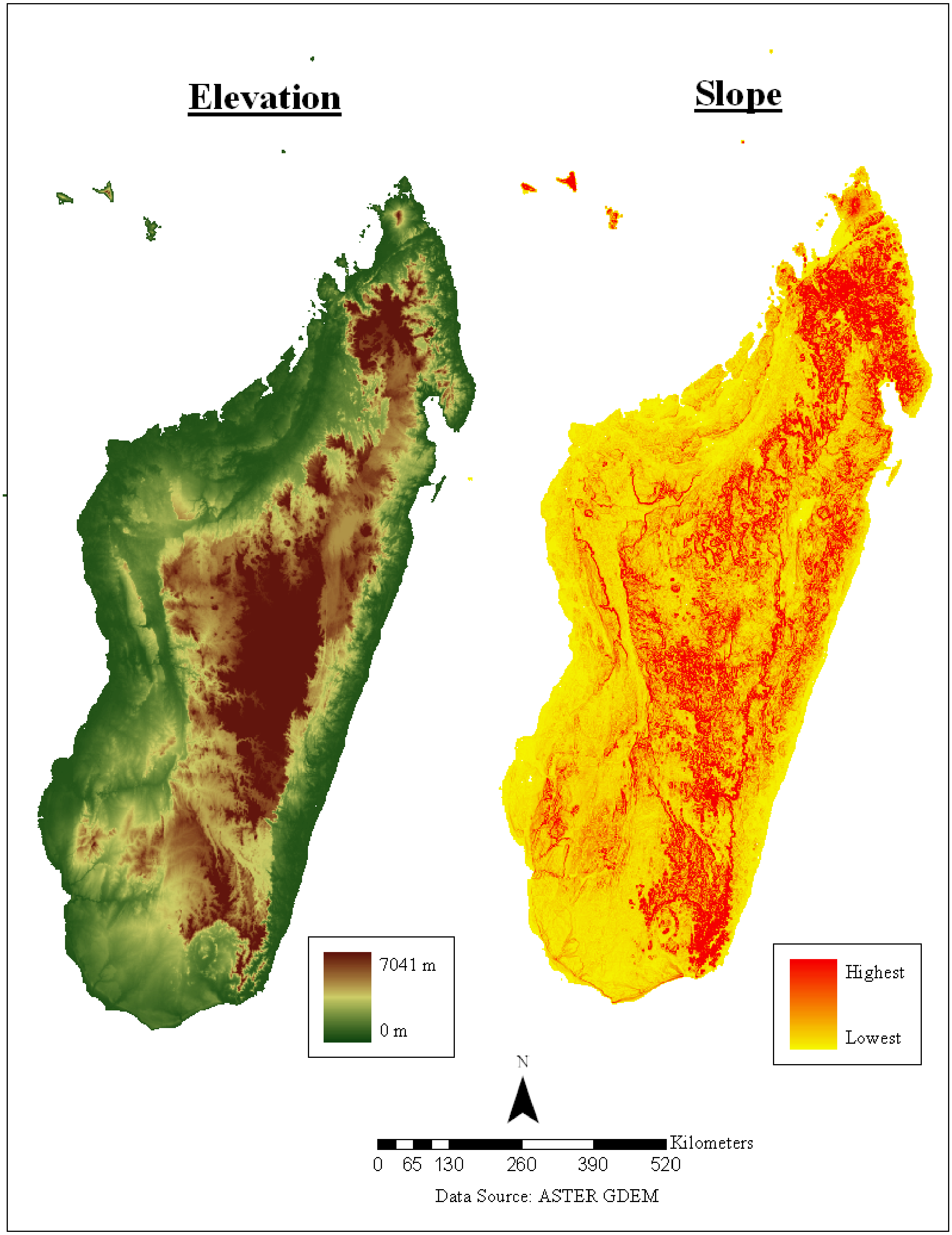


Figure 3.7: a) Digital elevation model; b) Slope derived from elevation

CHAPTER 4

MODELING ANALYSIS

The Madagascar Food Insecurity Index (FII) Model uses each of the variables as it relates to the three aspects of food insecurity: availability, access, and utilization. There are seven major model inputs: physical properties, agriculture, deforestation, underweight mothers, shocks, transportation, and household food expenditures. Availability is represented by transportation, shocks, deforestation, and agriculture; access is represented by household food expenditures as a percentage of income, shocks, deforestation, and physical properties; and utilization is represented by underweight mothers as a percentage of the population. Each of the layers was converted to a raster data set, which allows the model to use map algebra, a technique for the analysis of cartographic data (Tomlin, 1994). Map algebra lets the user perform mathematical calculations using operators and functions on the values of individual cells within input raster layers, and variables of an equation can be filled with map layers instead of individual values (Berry, 1987). Weights were also applied to each of the layers because some of the variables have more weight, as they are the primary contributors to food insecurity in Madagascar.

The social factors of agriculture, underweight mothers, and household food expenditures are each weighted at 15 percent. Deforestation and shocks are each weighted at 17.5 percent, as shocks can devastate the entire district quickly and deforestation is one of the primary focuses of the study. Transportation is weighted at 10 percent: because the roads are often impassable, their condition has a relatively small effect on the mostly rural population. Only major roads were available to this study. Inclusion of secondary/tertiary roads within this layer would be desirable for a larger scale or local study. This would allow for all transportation routes to be considered. Madagascar's population is 85 percent rural and routinely uses ox-drawn carts and walks to food distribution points. The physical properties are also weighted at 10 percent because human interaction through policies or aid support cannot change environmental characteristics such as amount of rainfall. Each of the variables is also categorized into availability, access, or utilization. That distribution is highlighted in Figure 4.1, the Madagascar FII model conceptual framework.

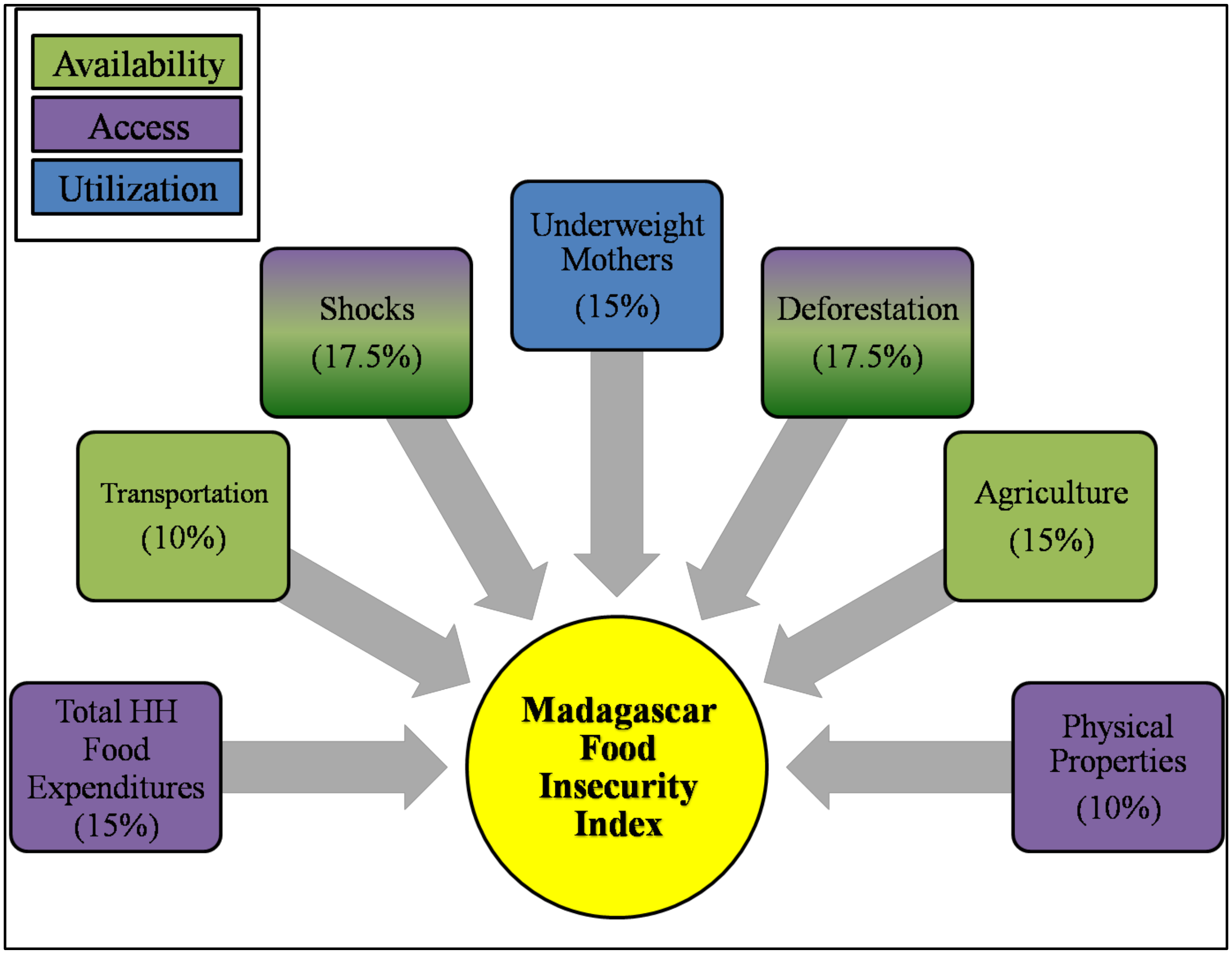


Figure 4.1: Madagascar FII model conceptual framework

Before the FII model was run, the soil erodibility, average monthly rainfall, and slope variables were combined with equal weights into one physical properties input of soil susceptibility. The physical properties layer served as an input to the Madagascar FII model and represent access as it relates to a household's ability to obtain food (through production or monetary income). The areas with the highest erosion would have difficulty cultivating food either to sell or to consume. The resulting map (Figure 4.2) indicates the areas most susceptible to soil erosion and thus of most limited food access. These areas occur along the eastern portion of the country where there are steeper slopes and more rainfall.

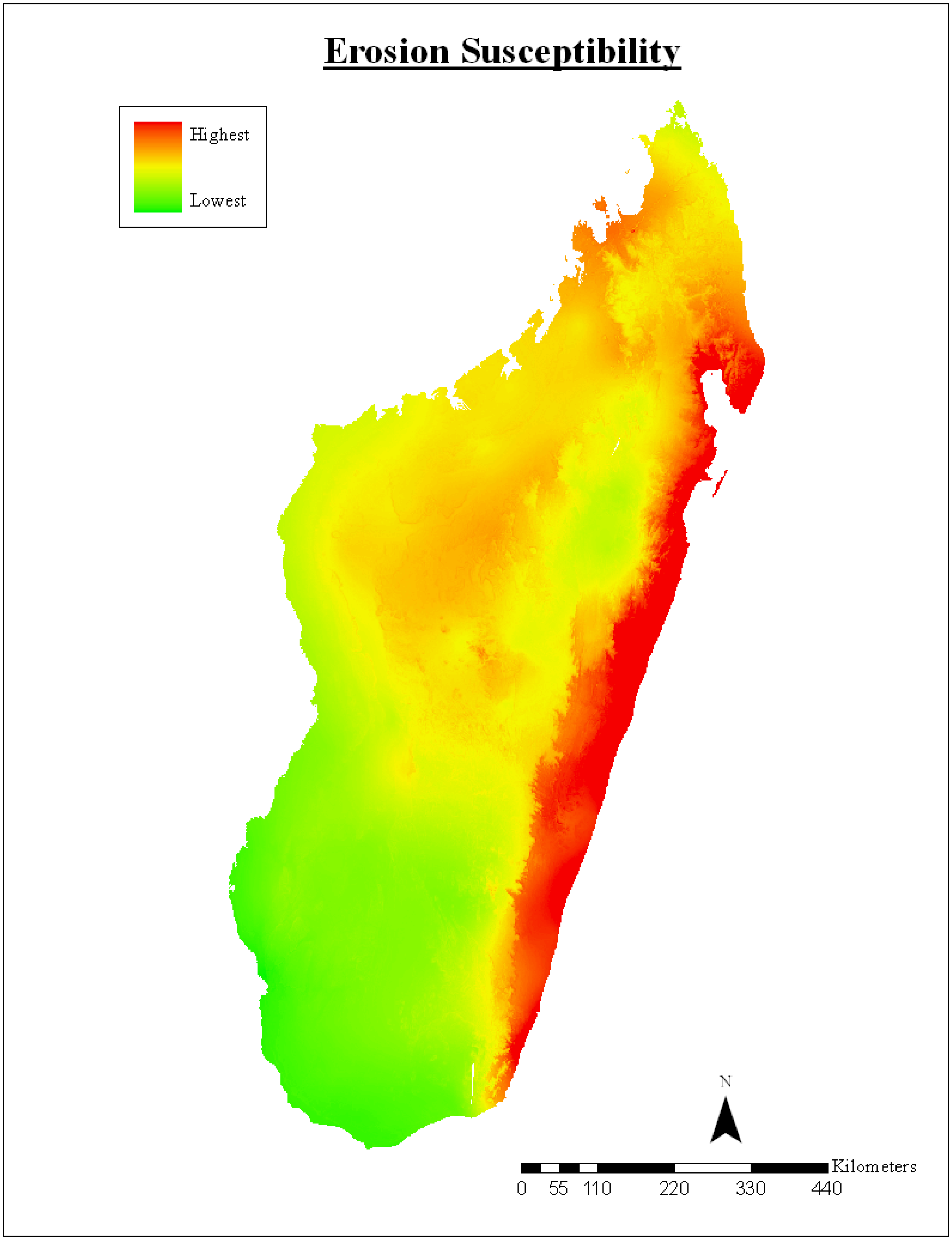


Figure 4.2: Final physical properties layer of erosion susceptibility

Once the physical properties (erosion susceptibility) layer of the FII was created, the remaining layers were added for the final depiction of access (household food expenditures, shocks, and deforestation), availability (transportation, shocks, deforestation, and agriculture), and utilization (underweight mothers) shown in Chapter 3 (Figures 3.3-3.8). These values were input to the ArcGIS Model Builder (see Figure 5.7). Using map algebra in ArcGIS, weights of the Madagascar FII model were applied to each layer's cell values and the raster layer of each variable was added to create the model output. The initial results of the model were reclassified using quintile divides (five classes) to create clearly ranked levels of food insecurity. The raster model output was then converted to a shapefile for cartographic display and further analysis at the Madagascar district level as shown in Figure 4.3.

A visual assessment of the Madagascar FII model results indicates three apparent clusters of the highest food insecure districts along the eastern coast as well as a small cluster in the south and an isolated high food insecure district in the middle and northern portion of the country. The most food secure areas are located within the western portion of the central highlands. This spatial pattern of food insecurity by district was further analyzed using spatial statistics to quantify the strength and significance of the spatial clusters. A discussion of the spatial pattern of model input layers of social factors and of land cover and other physical properties follows in Chapter 5 to provide a more complete picture of modeled food insecurity within Madagascar.

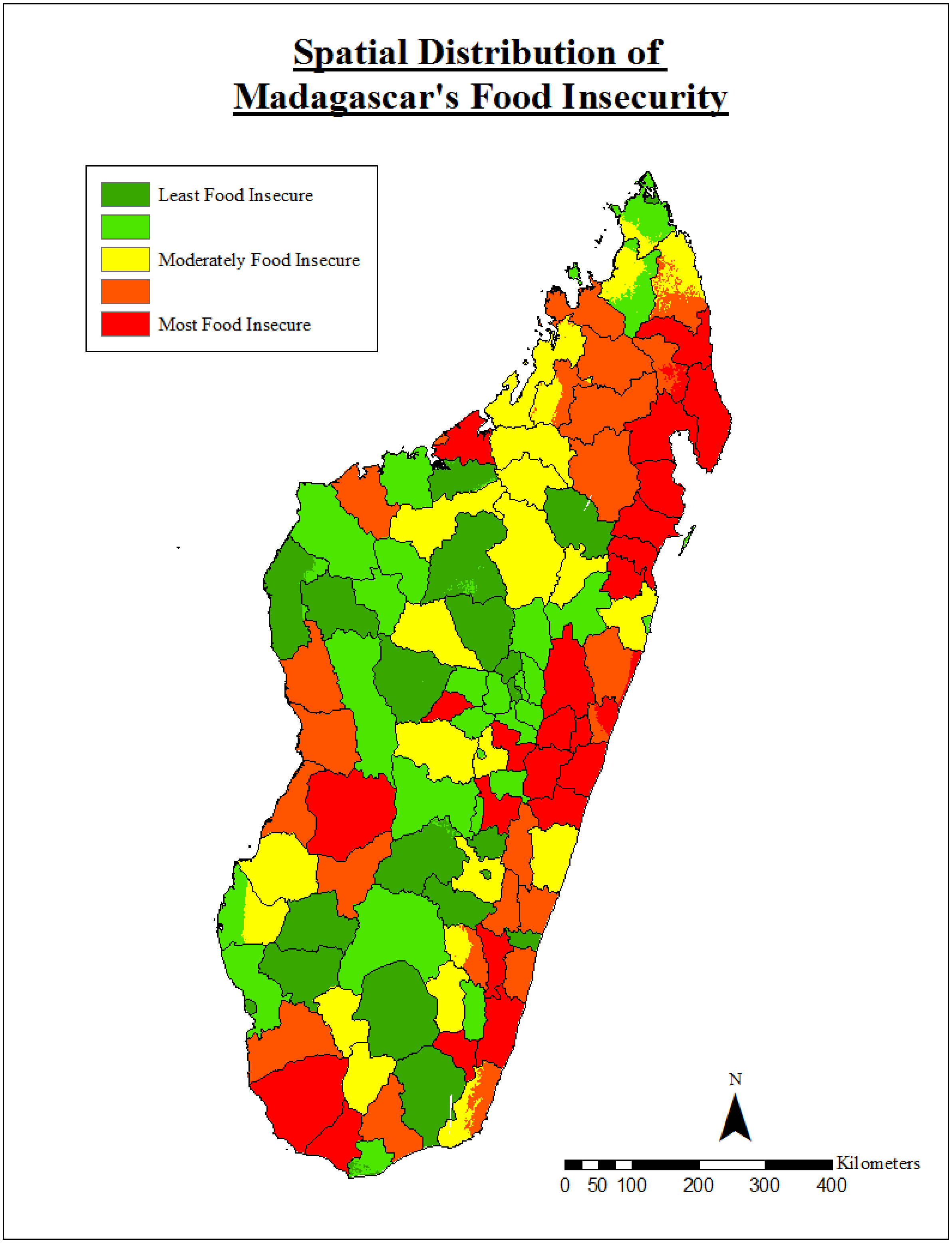


Figure 4.3: Final cartographic output of Madagascar FII Model showing the most food insecure areas within the country

CHAPTER 5

DISCUSSION OF MODELING COMPONENTS AND RESULTS

The ultimate goal of this thesis is the formation of the Madagascar Food Insecurity Index (FII) model. Close inspection of each contributing social and physical component, however, provides insight into the larger global food insecurity problem. In addition, analysis of the spatial pattern of each FII model component layer is valuable for understanding the causes and possible solutions of food insecurity. This chapter will discuss the components of the Madagascar FII—availability, access, and utilization—in terms of significance to the model and spatial pattern.

The statistical significance of apparent clusters of districts exhibiting particularly high levels of an individual social or physical factor was tested using the Moran's I Index. This index is commonly applied to spatial autocorrelation, a measure of how clustered or dispersed locations are based on their attribute data (Wong and Lee, 2005). For each model component variable, the Moran's I Index was calculated using ArcMap's spatial statistics tools. Results also include z-scores in terms of number of standard deviations to indicate how confident the researcher can be of the results. The greater the absolute value of the z-score, the greater the confidence that the results are not based on chance (Wong and Lee, 2005). For example, if the z-score is ±1.96, the results are interpreted as a significantly nonrandom cluster at a 95 percent confidence level, which is within two standard deviations. The degree to which the district level values of each component layer are either clustered or dispersed is depicted in a figure for each component, along with the significance level. In this way, visually apparent clusters of districts are statistically validated or confirmed in terms of spatial pattern. The spatial pattern of each component is then used to discuss possible significance for the model results and to propose potential solutions to the food insecurity problem in Madagascar.

Social Factors

The spatial distribution of the social factors clusters can be used to focus aid solutions, educational programs, or other types of intervention. For example, spatial clusters of **agriculture practices** are related to deforestation, loss of soil nutrients, and poor food availability. When analyzing the agricultural crops grown in Madagascar, rice is the primary cultivated crop. It accounts for the majority of Madagascar's cultivated areas, yet most farmers do not produce enough rice to feed their families. Most Malagasy farmers cultivate rice on valley bottoms and terraced hillsides, as well as in freshly cleared uplands. These practices play a significant role in the deforestation of the eastern lowland areas (WFP Madagascar, 2006). Using the Moran's I Index, the spatial distribution of the rice cultivation variable was found to be significantly clustered, with a Moran's I value of 0.33 and a z-score of 5.09. This means there is less than 1 percent likelihood that this pattern is the result of chance (Figure 5.1; see Figure 3.2a). This spatial distribution is explained by the intense farming in the eastern portion of the country that exploits low relief valley bottoms and moderate relief hills in the eastern zone of Madagascar.

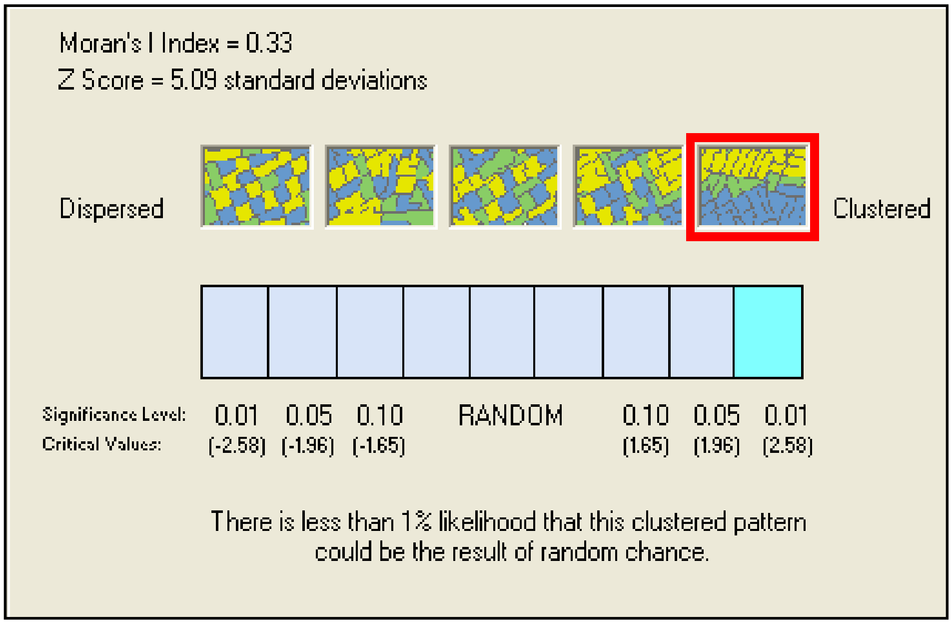


Figure 5.1: Moran's I spatial autocorrelation results for percent of the population involved in agriculture

In Madagascar, levels of **maternal malnutrition** are among the highest found in Sub-Saharan Africa. Nationally, 19 percent of the women are considered underweight. Chronic malnutrition is an indication of longer-term undernutrition and poor consumption (WFP Madagascar, 2006). With unhealthy mothers, the children of Madagascar are also underweight and suffer from acute malnutrition. This is an indication of an unhealthy and less productive adult population in the future and is the only component representing food utilization in the Madagascar FII model. Visually, there seems to be a clustering of high percentages of underweight mothers along the eastern portion of Madagascar (see Figure 3.2b). However, the spatial autocorrelation (Moran's I) test indicates the pattern is indeed random, with a value of 0.05 and a z-score of 0.85 (Figure 5.2). This lack of spatial pattern may be attributable to nonspatial contributing factors to material malnutrition, or, more likely, the ubiquitous condition of food scarcity throughout Madagascar.

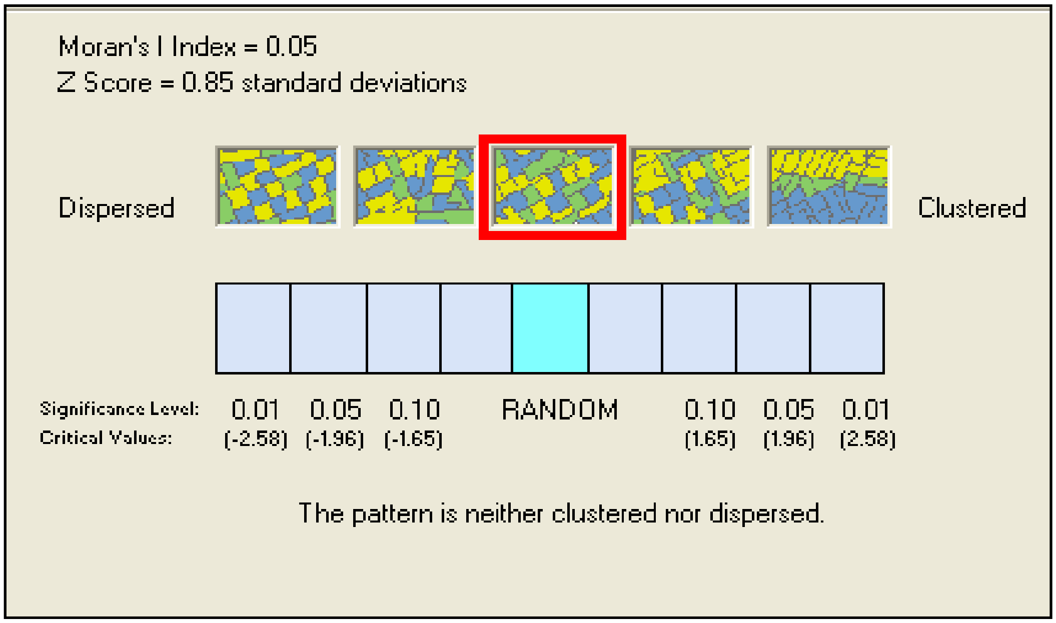


Figure 5.2: Moran's I spatial autocorrelation results for percent of the population constituted by underweight mothers

Economic situation and food insecurity are linked through the amount each household is able to spend on food, or percentage of the **household income spent on food**. Unfortunately, each political crisis in Madagascar paralyzes the national economy and increases governmental corruption. In 2002, for example, there was a 12 percent decrease in the gross domestic product, and Madagascar is still working to revive the economy (WFP Madagascar, 2006). The most important economic activity in the majority of Malagasy households is the marketing of crops. In the eastern zone, cash crops play the most important role, while the sale of animals and animal products is more important in the southern region. Therefore, the total household food expenditures would be expected to be more in the east and the south, as those areas are more susceptible to global food price fluctuations and shocks (natural and political). This is visually confirmed in Figure 3.2c, which shows that the highest percentages of income expended on food are found in the south and the east. The Moran's I test for spatial autocorrelation yields an index value of 0.19, indicating that this variable is highly clustered and there is less than 1 percent likelihood that the pattern is the result of chance (Figure 5.3). The z-score of this variable is 3, indicating that it is highly unlikely the distribution occurred due to chance.

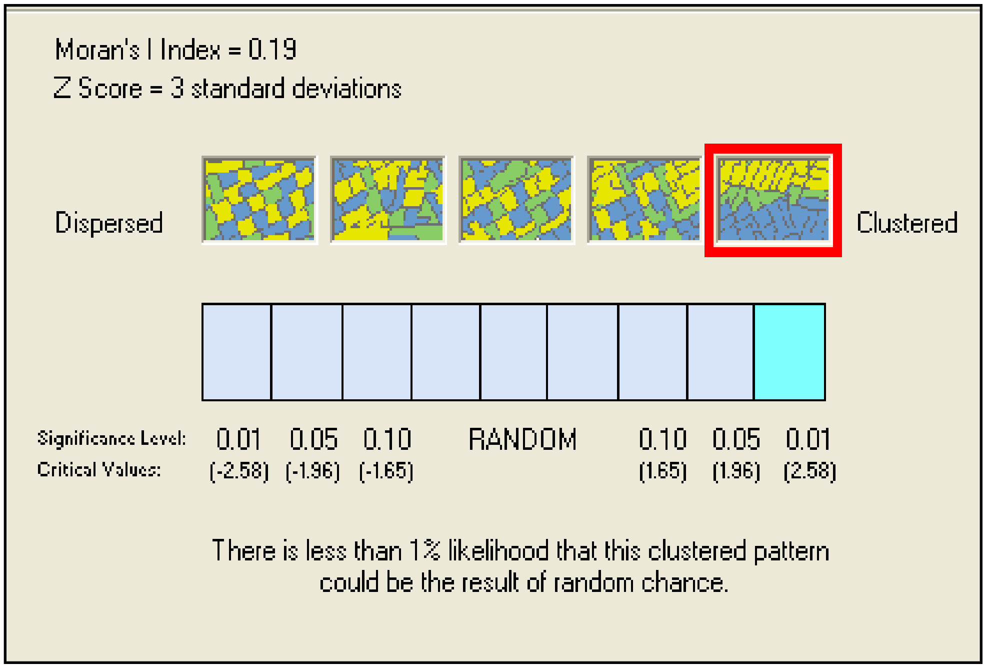


Figure 5.3: Moran's I spatial autocorrelation results for percent of household income expended on food

There are three main types of **shocks**: natural, social, and economic, with different areas of Madagascar susceptible to different types of shocks. The three main types of natural shocks are cyclones, floods, and droughts. However, soil degradation also is a natural shock that affects the areas where the land is primarily used for cultivating rice (eastern portion and to a lesser extent the central highlands) (WFP Madagascar, 2006). Social shocks, such as political coups, are rare, difficult to quantify, and usually not reported. Although economic shocks affect the entire nation, they are most strongly felt by farmers in times of fluctuation of global rice prices (WFP Madagascar, 2006). Depending on the region, households also create a dependency on the forest, borrow money for food, or buy food on credit (WFP Madagascar, 2006). The clusters of high shock areas, considering total natural, social, and economic shocks, are in the east, south, and northern periphery (see Figure 3.2d). The spatial autocorrelation results indicate a relatively strong value of Moran's I (0.19) and a highly clustered spatial pattern that is less than 1 percent likely to be the result of chance, a conclusion supported by the z-score (Figure 5.4).

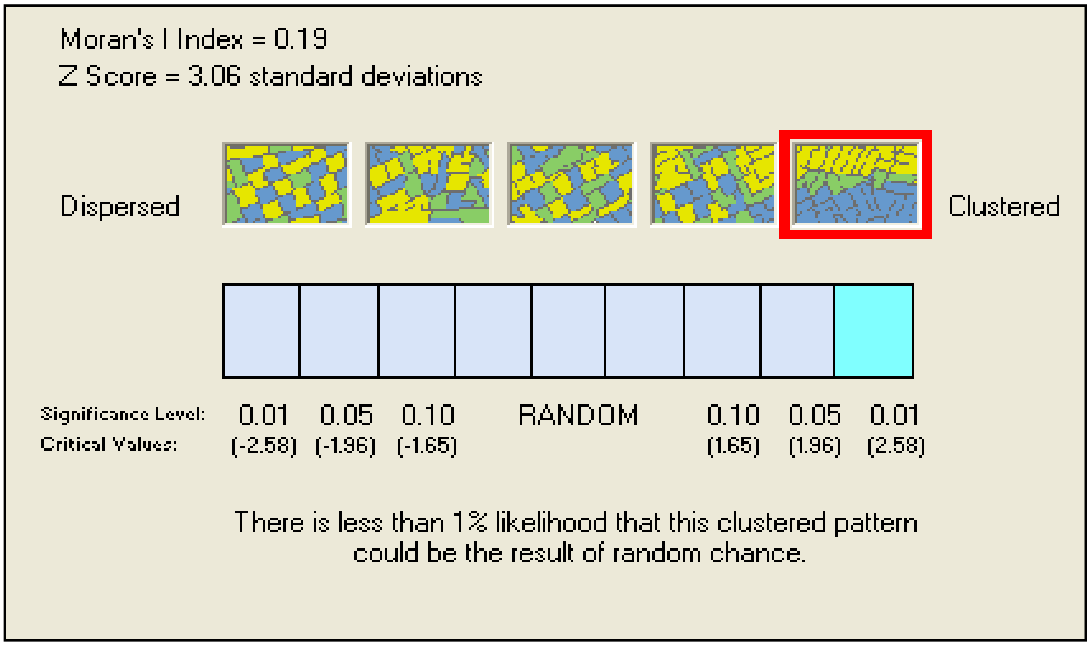


Figure 5.4: Moran's I spatial autocorrelation results for total shocks

<u>Deforestation</u>

Increasing frequency and magnitude of catastrophic natural events is associated with both global climatic change and environmental degradation, particularly the loss of forest cover (WFP Madagascar, 2006). The pattern of deforestation indicates whether conservation efforts are working or are merely a façade used to quiet external preservation pressures. Because deforestation within Madagascar has previously been documented in the literature (Green and Sussman 1990; Harper *et al.*, 2007), ascertaining its status was not the purpose of this research. However, this research did produce a new cartographic representation for the Harper et al. (2007) data and created a data set that can now be manipulated in a GIS and used to model food insecurity. The deforestation layer used in the Madagascar FII model represented the percentage of each district that had been deforested from 1970 to 2000, remotely sensed and classified on a 30 ×30 m pixel basis. This allowed the data to be aggregated to the district level, comparable to the spatial data sets of the social factors. Results indicate strong clusters of deforestation on the periphery of the island, where the majority of the forests are located (see Figure 3.6). The Moran's I value is 0.45, which is more than twice as high as that of the other layers. This, along with a z-score of 9.17, indicates a highly clustered spatial distribution not due to chance (Figure 5.5).

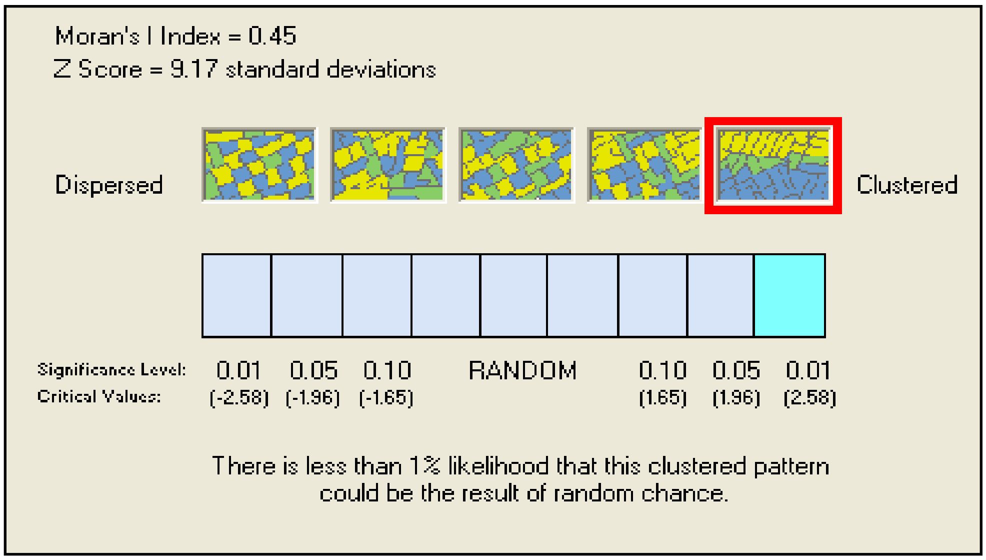


Figure 5.5: Moran's I spatial autocorrelation results for percent of the districts deforested

Physical Properties

Due to the spatially continuous raster format of the physical properties data layers, slope and rainfall alternative analysis from district-based cluster analysis was conducted. The physical properties and historical climatic records can be used to predict where the most soil erosion will occur on Madagascar. This information has the potential to create a sense of urgency within those areas to change their current land use practice in view of the relative food insecurity related to soil nutrient loss. Based on Figure 4.2 (erosion susceptibility map), the area most at risk is the eastern portion of the country. This area has the steepest slopes, receives the most rainfall, has the highest erosivity, and is deforested. Because it is most at risk for erosion and soil degradation, the ability of farmers along the eastern coast of Madagascar to produce food, either to sell or to consume, is most negatively impacted. Another area that is likely to experience erodibility problems is the northern portion moving south into the central highlands. This area also has steep slopes, and although it does not receive as much rain as the eastern zone, it does receive more rain than the southern region, which is the most stable. The regions with similar erodibility are most clearly indicated by the contours highlighted in Figure 5.6.

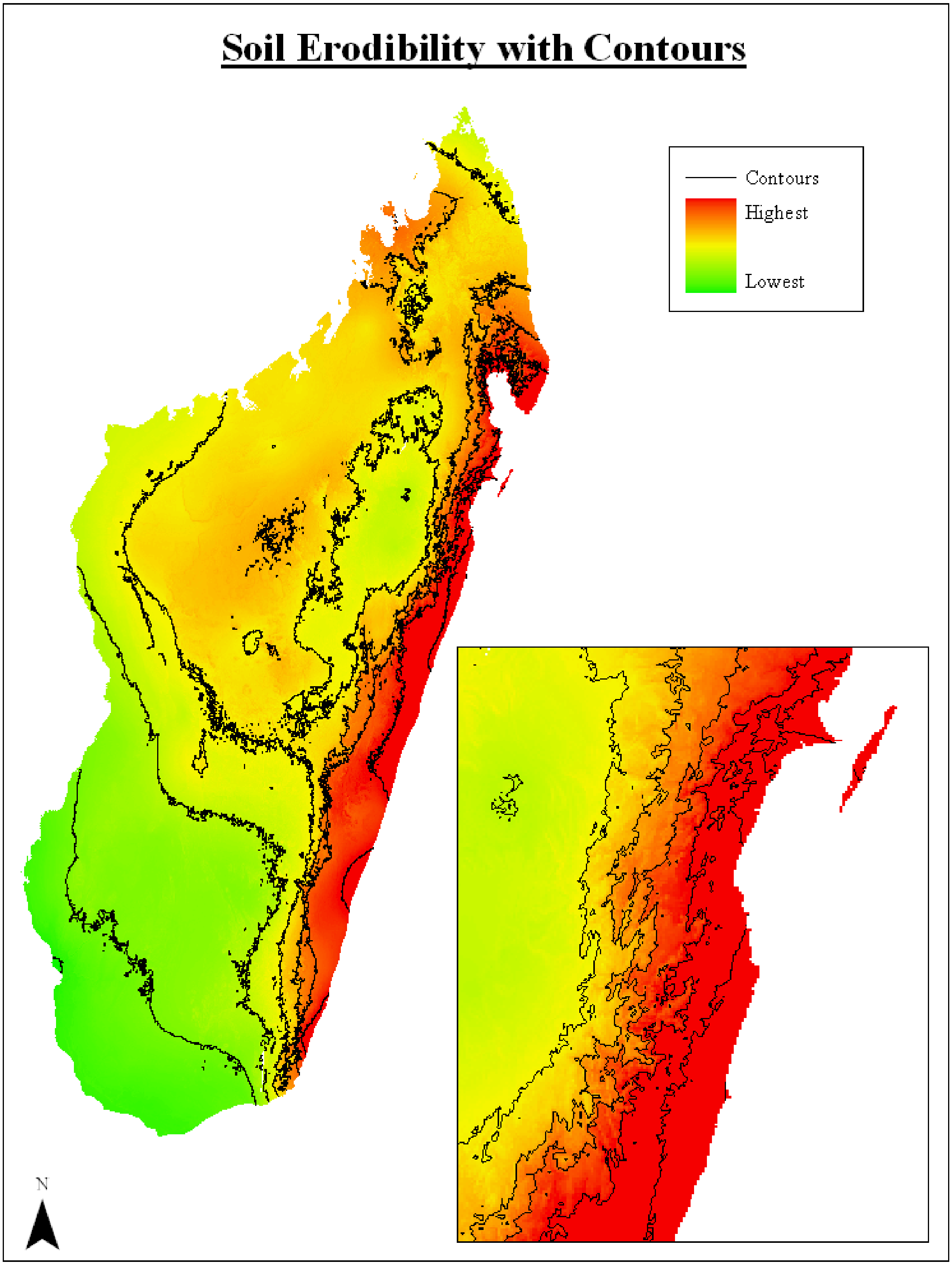
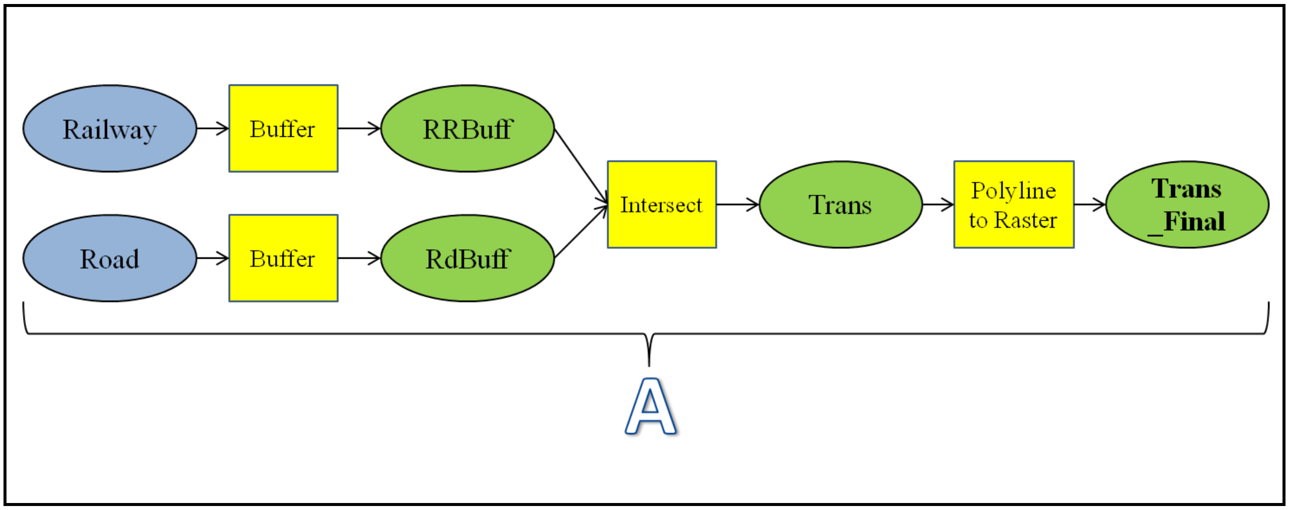
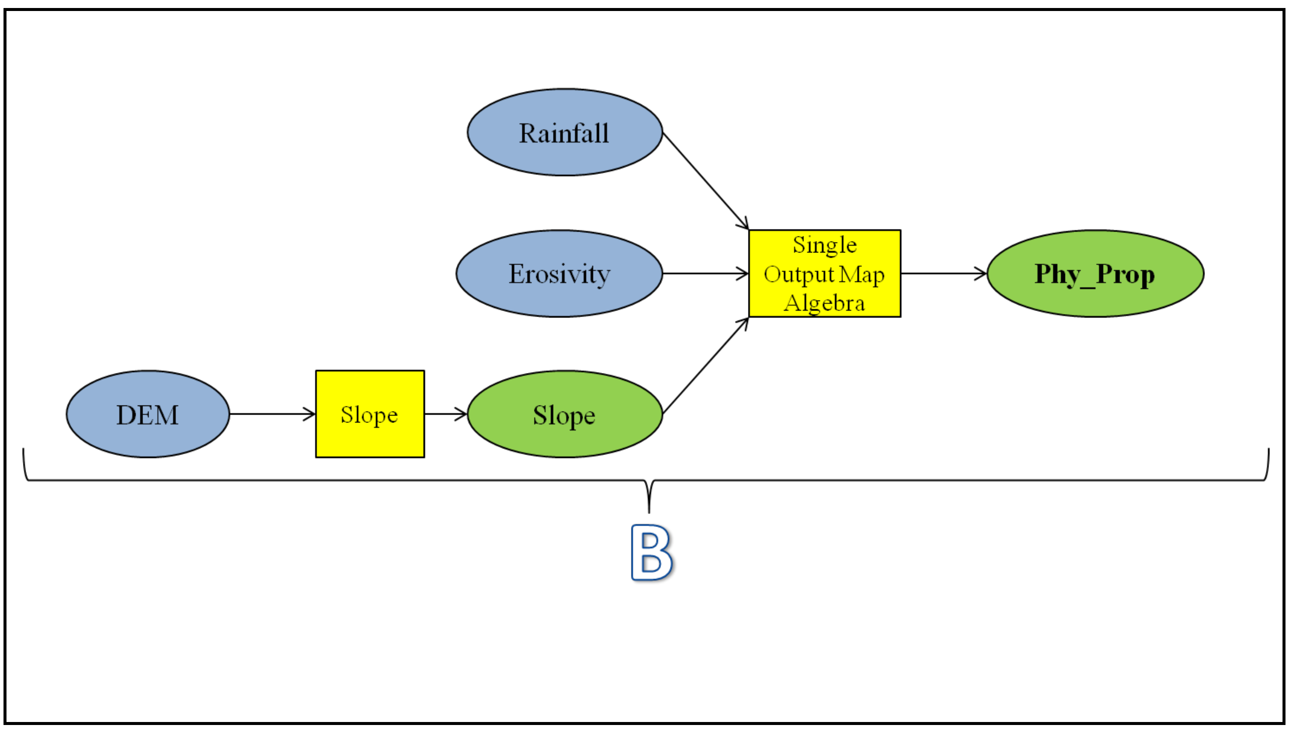


Figure 5.6: Soil erodibility with contours, indicating that the eastern portion of the island is most susceptible to erosion and soil degradation

Madagascar Food Insecurity Index Model

The Madagascar FII model was developed to spatially analyze the direct and indirect relationships among environmental and social factors influencing food insecurity. The model uses a variety of algebraic functions operating on raster layers with specific weights, which were then combined within a cartographic model framework implemented in ArcGIS (Figure 5.7).





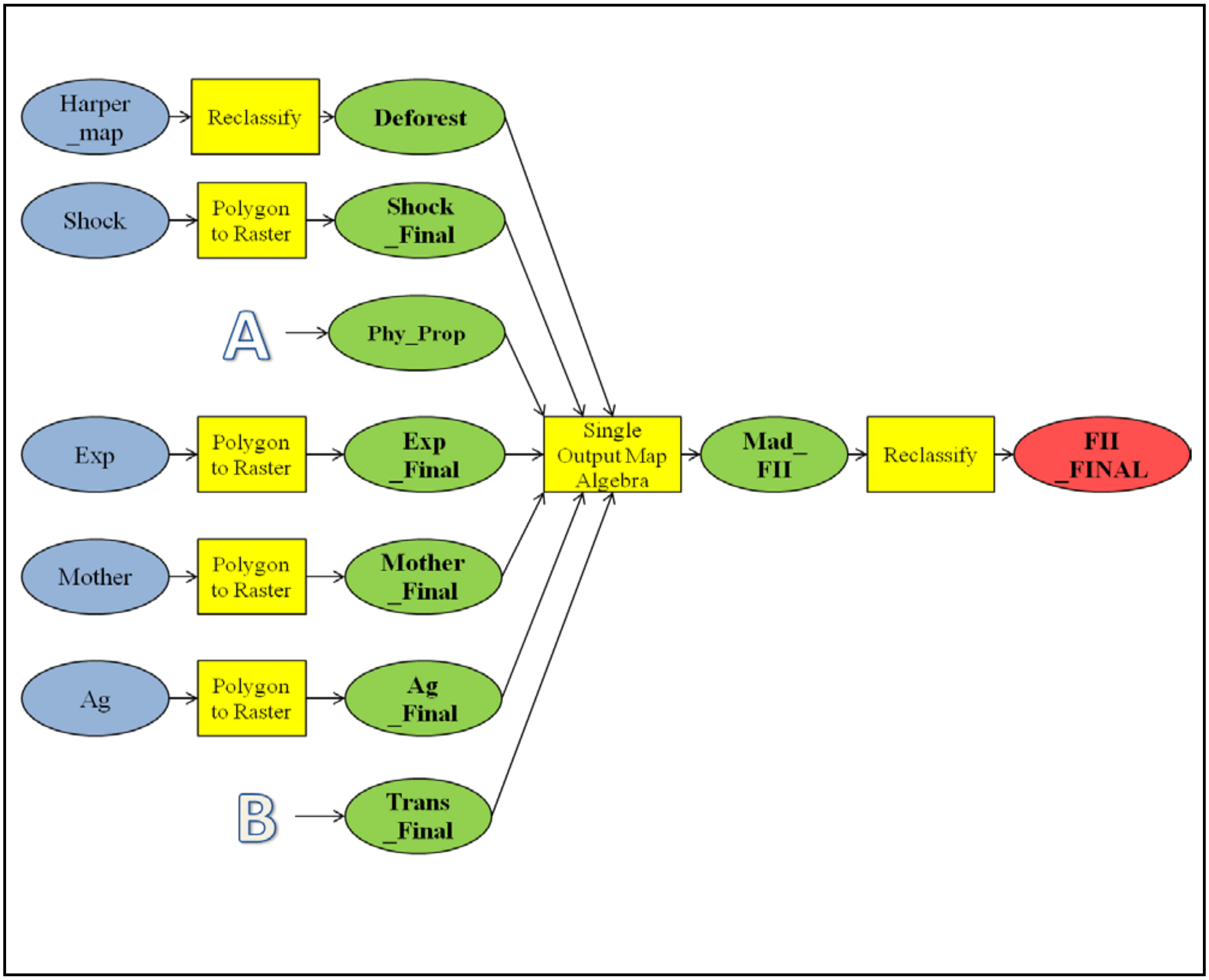


Figure 5.7: ArcGIS depiction of Madagascar FII model

The results of the Madagascar FII model provide a clear indication of where the most food insecure districts in Madagascar are located. The spatial autocorrelation test validated the apparent spatial clustering of districts with high food insecurity, with a Moran's I value of 0.51 and a z-score of 48.73 (Figure 5.8). As shown in Figure 4.3, there seems to be three clusters along the eastern coast, as well as one in the south and one in the north. Visually, the most food secure areas appear to be within the western portion of the central highlands.

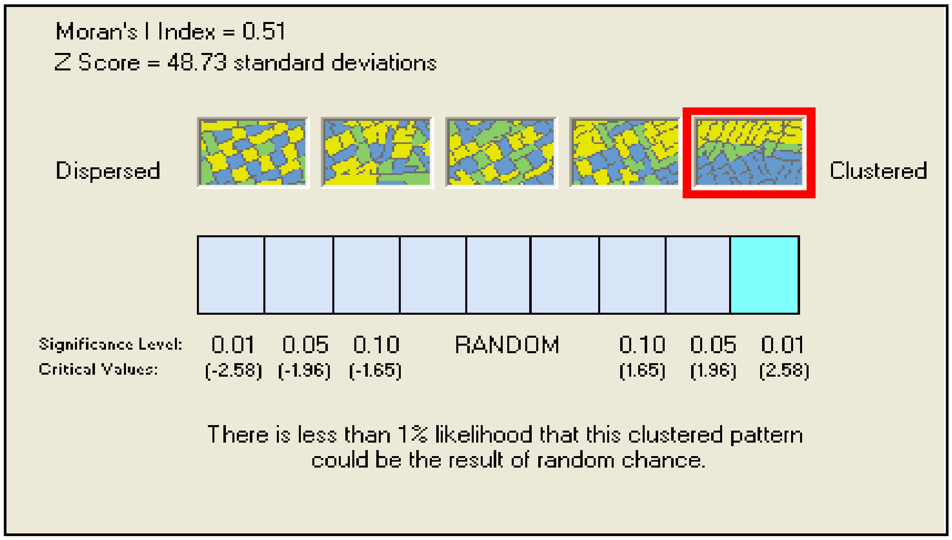


Figure 5.8: Moran's I spatial autocorrelation results for the Madagascar FII model output

In addition to the clustering, the amount of people affected by food insecurity is examined. The 2001 Madagascar Census district populations were used to determine the amount of people affected at each food insecurity level. The summary of the population distribution classification is listed in Table 5.1, and Figure 5.9 shows the percentages of food insecurity at each of the five levels. . Seventeen percent of the population has low food insecurity, 27 percent have low/moderate food insecurity, 16 percent have moderate food insecurity, 18 percent have moderate/high food insecurity, and 22 percent have high food insecurity affecting over 4 million people.

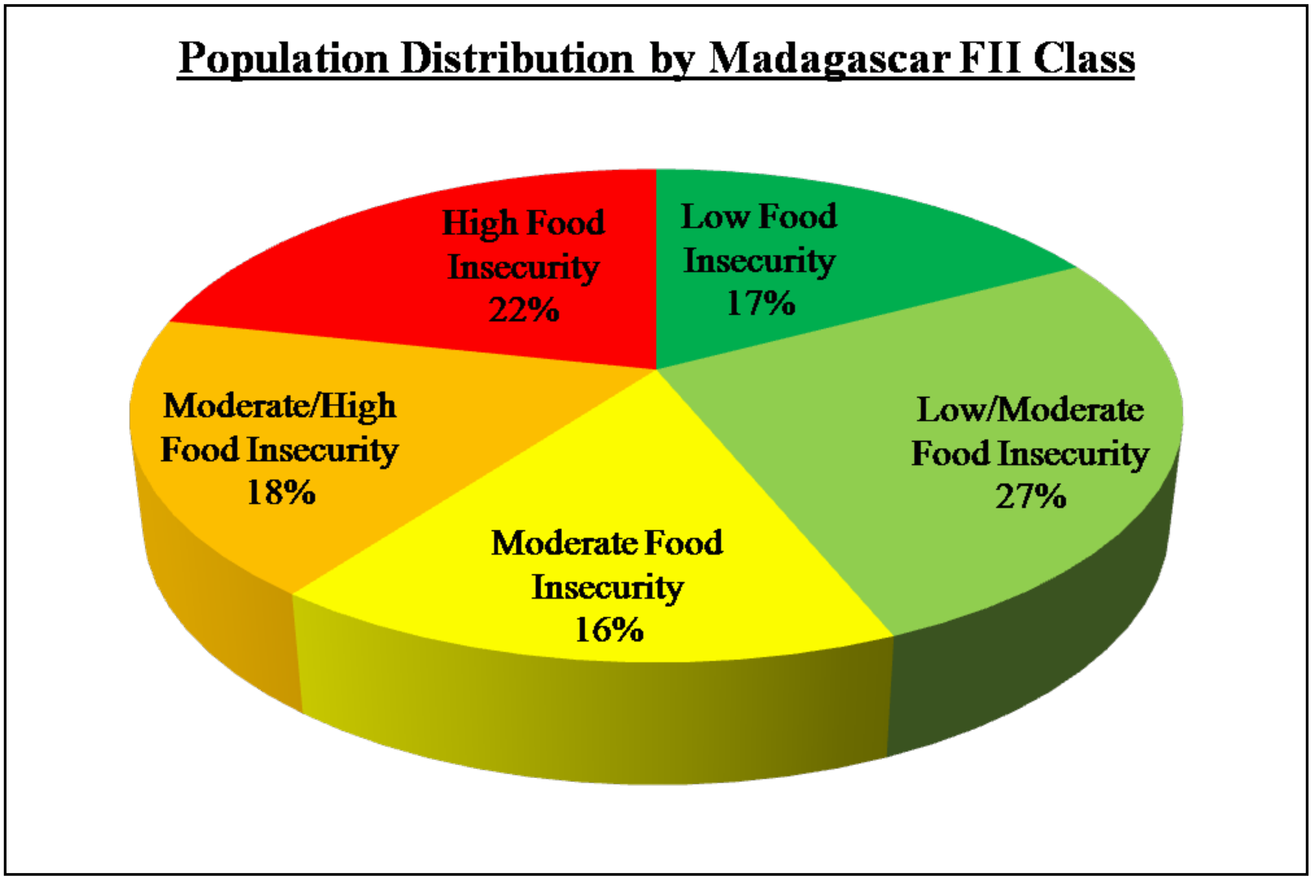


Figure 5.9: Population distribution by Madagascar FII class

Table 5.1: Total populations of Madagascar food insecurity levels

Food Insecurity Ranking	Population	Percent
Low	3511908	17.25
Low/Moderate	5406513	26.56
Moderate	3337246	16.39
Moderate/High	3699682	18.17
High	4403591	21.63

To better understand the distribution of food insecurity, a hot/cold spot analysis was conducted. While Moran's I Index measures only the spatial distribution of geographic data and not the attribute values of each location, hot/cold spot analysis assesses the significance of the attribute value as either high (hot) or low (cold) for each given cluster. This tool within ArcGIS helps users to understand the polygon values in relation to their neighbors and is often used to analyze spatial patterns. When determining what constituted a neighbor, the inverse distance relationship was utilized. This considers how the impact of one feature on another feature decreases with increased distance. The output, shown in Figure 5.10, indicates large hot spots in the north and east. This output would be extremely helpful for allocating resources on a provincial level (Madagascar has six provinces) or if a larger spatial resolution was desired by decision makers.

Based on the two previous studies (USAID and WFP), this Madagascar FII model output is most like the WFP results; however, there are still major differences. The WFP indicates that the southern and southwestern portions of Madagascar are the most food insecure, while the Madagascar FII indicates that the eastern and northeastern regions are the most food insecure. The latter indicates some districts in the south and southwest as food insecure, but the overall trend is not the same (Figure 5.11). This difference is attributable to the larger number of variables considered within the Madagascar FII model: the inclusion of social, physical, and land use components makes this model unique in the study of food insecurity within Madagascar. Table 5.2 is a summary of the variables considered within each study. The results of the Madagascar FII model are logical, as the spatial clustering of the physical factors and deforestation both indicate that the most food insecure areas would be the eastern and southern zones.

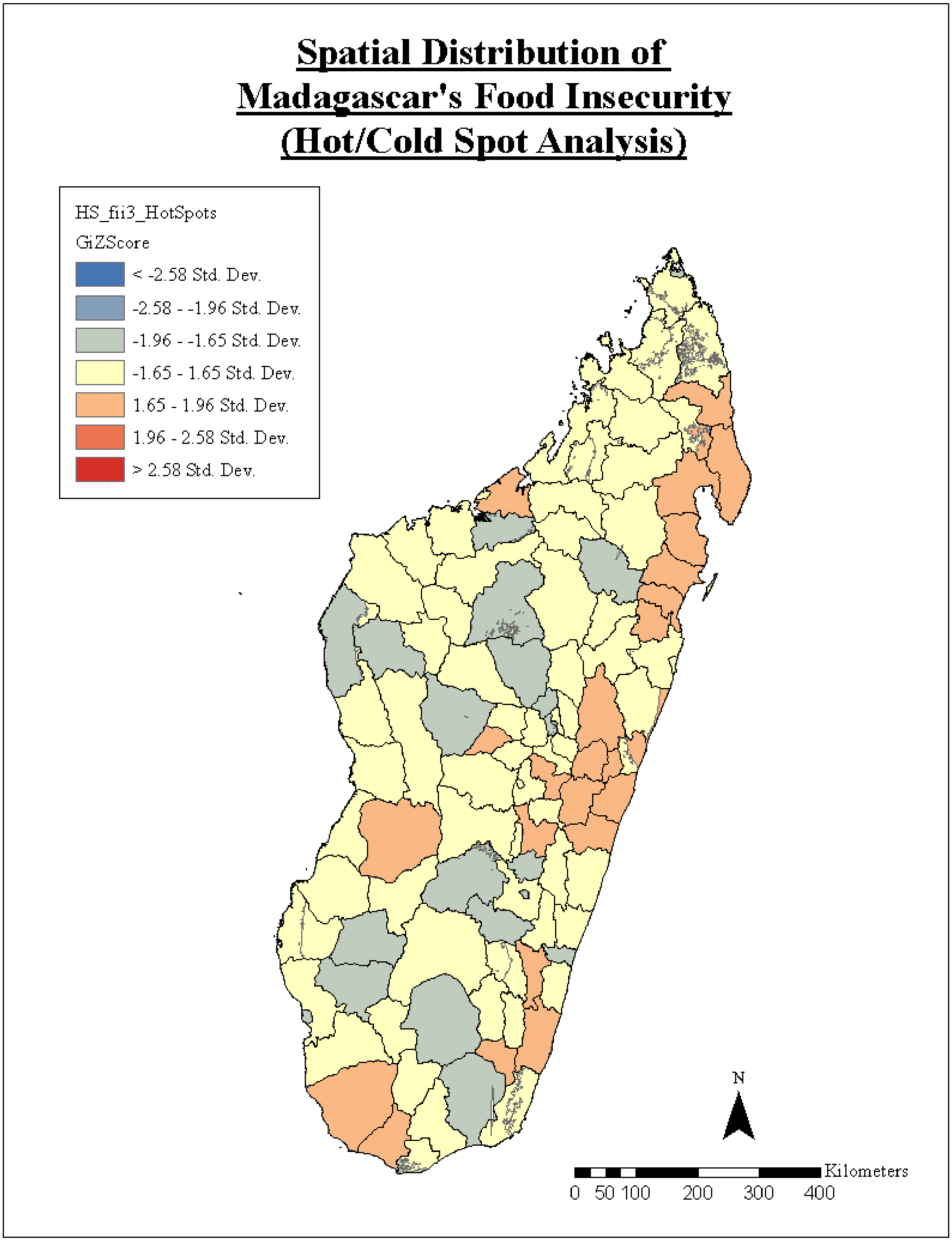


Figure 5.10: Hot/cold spot analysis of Madagascar's food insecurity

Table 5.2: Summary of the variables considered within each study

Model	Variables
USAID	Percent of children stunted
	Percent of population living under $1/day
	Percent of population undernourished
WFP	Insufficient rainfall
	Chronic malnutrition
	Literacy
	Underweight
	Agriculture population
	Chronic cyclone index
	Number of female headed households
Madagascar FII	Percent Population in Agriculture
	Total Household Food Expenditures
	Underweight Mothers
	Total Shocks
	Roads
	Railroads
	Deforestation
	Average Precipitation
	Digital Elevation Model
	Soil Erodibility

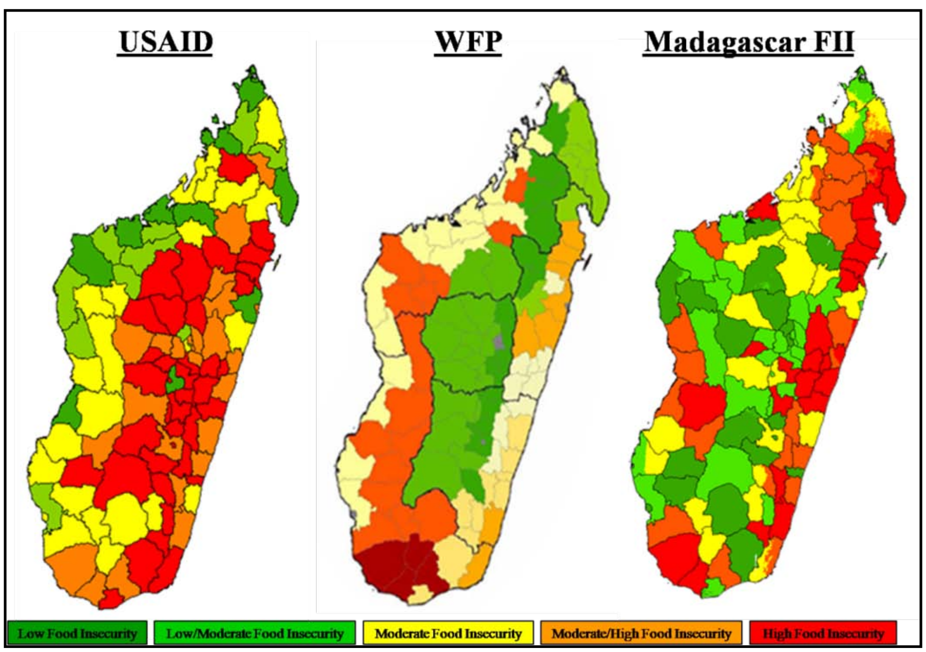


Figure 5.11: Comparison of major spatial Madagascar food insecurity distribution studies

CHAPTER 6

SUMMARY AND CONCLUSIONS

This study had three objectives. The first encompassed the social factors of the FII, and the second focused on the deforestation input component. The third objective used the social factors and deforestation to design and create a more comprehensive food insecurity index (FII) for Madagascar using a cartographic model of social and physical factors as well as land cover. The following is a summary of the results of all three objectives.

In order to seat the Madagascar FII model within previously conducted work, the USAID FII conceptual framework was used as a guide. This framework demonstrated the need for sociological variables and identified the lack of environmental inputs in previous assessments of Madagascar food insecurity. The data sets used for this social section of the model were derived from the 2001 Madagascar Census: 1) percentage of population in agriculture; 2) percentage of household income expended for food; and 3) percentage of the population constituted by underweight mothers. Each of those variables represented one of the factors contributing to food insecurity: availability, access, and utilization.

Upon creation of the social factor data layers for inputs to the Madagascar FII model, it was found that each variable has a different spatial distribution. The percentage of the population involved in agriculture was highly clustered and focused along the eastern coast. This clustering represents the rice cultivation practiced in the tropical zone running along the eastern coast. The second variable, mothers who are underweight, was randomly distributed and did not display any clustering. This is reasonable, since malnutrition is a national problem affecting all women regardless of location. The last social variable is percentage of household income expended on food. This, like percentage of the population involved in agriculture, is highly clustered, with the clusters located in the southern and northeastern parts of the island. Included with the social factors are total shocks and transportation. These two variables also can be classified as affecting food access and availability. The shock layer is the total number of shocks a household received in the past year. Although the variety of the shocks is different throughout the country, the effect of decreased food access and availability is the same. The distribution of shocks is highly clustered and focused in the east, south, and northern periphery of Madagascar. The transportation network is minimal, with the main artery running through the center of the island from north to south. This provides limited access in terms of food and goods distribution.

The second objective was to assess the current status and trends in Madagascar's deforestation to determine spatial variability and integrity of forest cover and soil condition. This was done in two phases. The first involved determining which districts were the most deforested based on percentage of total area, and the second incorporated some environmental variables to determine the soil erosion susceptibility.

In order to determine which areas of Madagascar are the most deforested, the Harper et al. (2007) deforestation map was scanned, automatically classified, and postprocessed to refine the data set. The resultant data layer indicated that the most deforested areas are on the outer edge of the island with concentrations in the north and south. This pattern occurred because prior to the study (1970-2000) most of the eastern coast was already heavily involved in rice cultivation, whereas the northern and southern areas are only now being deforested for agriculture and charcoal production. The second part of this objective involved the physical properties of the island and how they influence the soil quality. The properties included soil erodibility, monthly precipitation, and slope. Each variable was downloaded and manipulated to fit the study area. Using map algebra, the physical properties variables were combined to form the erosion susceptibility layer, which is called "physical properties" in the final Madagascar FII model.

The final objective was to use the first two objectives' results, as well as map algebra, to develop a model to analyze the direct and indirect relationships among environmental and social factors influencing food insecurity. This was achieved using map algebra with a cartographic final output. There were a total of seven variable inputs, each representing availability, access, or utilization. Both shocks and deforestation represented access and availability, as they influence more than one factor of food insecurity. This model achieved its purpose of identifying the most food insecure districts. Application of the model ascertained that the most food insecure areas are along the eastern coast as well as a few districts in the south. This study is a unique and valuable contribution to the literature because it incorporates a wider array of variables than the USAID and WFP studies and used spatial statistics rather than classical statistics to examine the significance of apparent spatial patterns. This model's usefulness stems from the nature of food insecurity as not only a social problem, but also as heavily influenced by the physical environment. On a regional scale, the Madagascar FII model results reflect the general trends produced by the WFP model; however, there are differences within the districts. Because it incorporates social as well as physical factors, the Madagascar FII model is more robust and provides a more complete picture of the spatial distribution of food insecurity within Madagascar.

Future Model Testing and Applications

Further research should be devoted to testing the Madagascar FII model through a sensitivity analysis of the variables chosen and their relative weights. Although noted as an important and necessary step in modeling, due to time constraints sensitivity analysis was not conducted in this study. A verification of the model is also important. This could be done through ground testing or an in-depth discussion with NGOs currently working in the area, as well as with Malagasy governmental organizations. Results of this study indicate that the model may be improved by incorporating more categorical divisions within the variables or including more variables such as aid distribution, rural/urban distinction, and a complete land cover analysis. Complete, repetitive, and timely census data would assist in testing the model's accuracy and could be used to monitor any changes to food insecurity.

Because this model is broad and incorporates many factors, it has numerous applications. This spatial model includes social and physical components that can serve as a baseline for future food insecurity studies within Madagascar and other parts of the world. Many countries suffer from food insecurity as a result of land cover change, environmental degradation, political or natural shocks, or an unstable economy: for example, India, Brazil, Haiti, and Indonesia. These countries could use this model to assist in identifying the most food insecure regions. That a similar model is not already being applied may be attributable to the lack of consistent and reliable data, to problems that arise from measuring short term versus long term shocks (e.g., earthquake versus increase in sea level), or to researchers and governments being satisfied with the current food insecurity models.

The Madagascar FII model could also influence the distribution of aid both from NGOs and from internal Malagasy assistance programs. It could be used by decision makers to determine new government policies as well as educational programs. Visual analysis indicates that the distribution of food security follows the road network: the least food insecure areas and the major national road lie in the central zone of Madagascar. Generally, the most food insecure areas fall in the most forested areas or the areas with the highest biodiversity. This model identifies areas where food insecurity is most severe and thus the areas most appropriate for action to address this critical issue.

Conclusions

While the unique flora and fauna of Madagascar enjoy global prominence, it is the underexplored relationship of its people, food insecurity, and deforestation that is the focus of this study. Specifically, this research sought to create a spatial model to examine the relationships between social factors, physical properties, deforestation, and food insecurity through an examination of their spatial distributions and patterns. Objective 1 was creation of a food insecurity index, which was completed using the USAID model as a conceptual framework. The food insecurity component was finalized and analyzed prior to the input of variables into the model, with all of the variables falling into access, availability, or utilization depending on what part of food insecurity the variable impacts the most. Objective 2 pertained to the deforestation and environmental properties of Madagascar. It was accomplished using the Harper et al. (2007) deforestation map as the basis of a reclassification of ranked percentage of district deforested. Once the most deforested districts were identified, they were used as input to the Madagascar FII model. To make the model more inclusive, additional social and physical properties were included. The final objective was to take the component inputs and utilize them in a spatial model with a cartographic output of the distribution of food insecurity in Madagascar. The variables chosen for this model were appropriate and reasonable based on their influence on food insecurity.

The Madagascar FII model result identified the most food insecure areas as being in the eastern portion of the country. This information provided by the model output can be used to inform public policy and social programs, which will enable them to address the more complicated issues involving food insecurity. This integrated analysis of spatial variables associated with food insecurity using a GIS approach demonstrated the application of change detection and spatial statistics to broad areas and made a contribution to research methodological tools that bridge the traditional fields of human geography and geospatial techniques. The incorporation of social factors to assess food access, availability, and utilization in a spatial GIS context has been little utilized in food security studies; spatiotemporal data analysis typically has been applied to physical processes and/or resource management. The Madagascar FII model actually contains aspects of social, physical, and biological phenomena that intersect in geographic space to produce insecurity in food access, availability, and utilization. The dynamic nature of food insecurity varies from the dramatic consequences of episodic disaster events to long-term gradual losses of access to plentiful food due to soil erosion and nutrient depletion over time. Although each of the five levels of food insecurity in Madagascar (low to high) occurred in approximately 20 percent of the land area, statistical analysis of the spatial pattern of food insecurity by district found the higher levels to be significantly clustered, especially along the eastern coast. Results of the Madagascar FII model in this study show areas of equal risk due to high potential for shocks (east coast), gradual soil degradation and loss (deforested periphery, especially eastern and southern zones), and decreased available food due to insufficient road network (central zone). It is hoped that the identification of hot spots of high food security will help to target remediation efforts and streamline relief distributions of food during times of political crisis and natural disasters.

REFERENCES

Agarwal, D.K., J.A. Silander Jr., A.E. Gelfand, R.E. Dewar, and J.G. Mickelson Jr., 2005. Tropical deforestation in Madagascar: Analysis using hierarchical, spatially explicit, Bayesian regression models, *Ecological Modeling*, 185:105-131.

Bakoariniaina, L.N., T. Kusky, and T. Raharimahefa, 2006. Disappearing Lake Alaotra: Monitoring catastrophic erosion, waterway silting, and land degradation hazards in Madagascar using Landsat imagery, *Journal of African Earth Sciences*, 4:241-252.

Bergeron, G., 2002. *Food Security in Madagascar: A Situation Analysis*. Washington, D.C.: Academy for Educational Development, Washintgon, D.C., 110 p.

Berry, J.K., 1987. Computer-assisted map analysis: Potential and pitfalls, *Photogrammetric Engineering and Remote Sensing*, 53(10):1405-1410.

Berry, J.K., 2009. GIS modeling frameworks, *Manual of Geographic Information Systems* (Marguerite Madden, editor), American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 527-585.

Bohra, A., and H. Andrianasolo, 2001. Application of GIS in modeling of dengue risk based on sociocultural data: Case of Jalor, Rasthan, India, *Dengue Bulletin*, 25:92-102.

Bolstad, P., 2008. *GIS Fundamentals: A First Text on Geographic Information Systems*, 3rd ed., Eider Press, White Bear Lake, Minnesota, 619 p.

Butler, J.S., and C. Moser, 2007. Cloud cover and satellite images of deforestation, *Land Economics*, 83(2):166-173.

Butler, R.A., 2008. Madagascar overview, URL: http://www.wildmadagascar.org/, Wild Madagascar (last date accessed: 10 November 2009).

Chomitz, K.M., and D.A. Gray, 1996. Roads, land use, and deforestation: A spatial model applied to Belize, *The World Bank Economic Review*, 10(3):487-512.

CIA World Factbook, 2008. Facts about Madagascar: The economy, URL: http://countrystudies.us/madagascar/21.htm, CIA World Factbook (last date accessed: 10 November 2009).

Cornell University, 2009. Data, URL: http://www.ilo.cornell.edu/ilo/data.html, Ilo, Ithaca, New York (last date accessed: 10 November 2009).

Dostie, B., S. Haggblade, and J. Randriamamonjy, 2002. Seasonal poverty in Madagascar: Magnitude and solutions, *Food Policy*, 27:493-518.

ERDAS, 1999. *ERDAS Online Field Guide*, 5th ed., ERDAS, Inc., Atlanta, Georgia, 672 p.

Fitz, H.C., 2002. Everglades landscape model high-level metadata, URL: http://www.likbez.com/AV/Spatial_Modeling_Book/6/struct/detail/metadata/graphics/ELMmetadata2.1a.pdf, South Florida Water Management District (last accessed: 22 February 2010).

Gade, D.W., 1996. Deforestation and its effects in highland Madagascar, *Mountain Research and Development*, 16(2):101-116.

Giles, P.T., and J.M. Burgoyne, 2008. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Progress in Physical Geography*, 32(5):575-580.

Green, G.M., and R.W. Sussman, 1990. Deforestation history of the eastern rain forests of Madagascar from satellite images, *Science, New Series*, 248(4952):212-215.

Green, R.H., 1987. Sub-Saharan Africa: Poverty of development, development of poverty, *Poverty, Development and Food* (E. Clay and J. Shaw, editors), The Macmillian Press Limited, London, England, pp. 78-111.

Harper, G.J., M.K. Steininger, C.J. Tucker, D. Juhn, and F. Hawkins, 2007. Fifty years of deforestation and forest fragmentation in Madagascar, *Environmental Conservation*, 34(4):325-333.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas, *International Journal of Climatology*, 25:1965-1978.

Honzak, M., and K. Wendland, 2007. Mapping and evaluating the benefits of hydrological services in Madagascar, River Symposium, URL: http://www.riversymposium.com/2007_Presentations/B3G_Honzak.pdf, Conservation International (last date accessed: 18 February 2010).

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman, 2008. *Remote Sensing and Image Interpretation*, 6th ed, John Wiley & Sons, Inc., Hoboken, New Jersey, 756 p.

Longley, P.A., M.F. Goodchild, D.J. Maguire, and D.W. Rhind, 2009. Geographic information science, *Manual of Geographic Information Systems* (Marguerite Madden, editor), American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 19-25.

Lucas, R.M., A.A. Held, S.R. Phinn, and S. Saatchi, 2004. Tropical forests, *Remote Sensing for Natural Resources Management and Environmental Monitoring: Manual of Remote Sensing*, 3rd ed., Vol. 4 (Susan Ustin, editor), John Wiley & Sons, Inc., Hoboken, New Jersey, pp. 239-315.

Mertens, B., and E.F. Lambin, 1997. Spatial modeling of deforestation in southern Cameroon, *Applied Geography*, 17(2):143-162.

Millward, A.A., and J.E. Mersey, 1999. Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed, *Catena*, 38:109-129.

Minten, B., and M. Zeller, 2000. *Beyond Market Liberalization: Welfare, Income Generation and Environmental Sustainability in Rural Madagascar*, Ashgate, Aldershot, England, 278 p.

Nelson, R., and N. Horning, 1993. Cover forest/non-forest classification of Madagascar from AVHRR data, *International Journal of Remote Sensing*, 14(8):1463-1475.

OneWorld, 2005. Chronically hungry people on the rise, URL: http://us.oneworld.net/article/chronically-hungry-people-rise, OneWorld (last date accessed: 10 November 2009).

Paine, D.P., and J.D. Kiser, 2003. *Aerial Photography and Image Interpretation*, 2nd ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 632 p.

Rakotosamimanana, B., 2003. Foreword, *The Natural History of Madagascar* (S.M. Goodman and J.P. Benstead, editors), The University of Chicago Press, Chicago, Illinois, pp. xi-xii.

Robiglio, V., W.A. Mala, and M.C. Diaw, 2003. Mapping landscapes: Integrating GIS and social science methods to model human-nature relationships in southern Cameroon, *Small-scale Forest Economics, Management and Policy*, 2(2):171-184.

Roy, A.H., 2003. Fertilizer needs to enhance production—Challenges facing India, *Food Security and Environmental Quality in the Developing World* (R. Lal, D. Hansen, N. Uphoff, and S. Slack, editors), Lewis Publishers, New York, N.Y., pp. 53-68.

Skole, D., and C. Tucker, 1993. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science*, 260(5116):1905-1910. Quoted in Giles and Burgoyne, 2008.

Thompson V. and R. Adloff, 1965. *The Malagasy Republic, Madagascar Today*, Stanford University Press, Stanford, California, 468 p.

Tomlin, C.D., 1990. *Geographic Information Systems and Cartographic Modeling*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 256 p.

Tomlin, C.D., 1994. Map algebra: One perspective, *Landscape and Urban Planning*, 30:3-12.

UNICEF, 2008. *UNICEF Humanitarian Action Report 2008*, United Nations Children's Fund, Geneva, Switzerland, 228 p.

United Nations Development Program (UNDP), 2008. Statistics of the human development report, URL: http://hdr.undp.org/en/statistics/, Human Development Reports, New York, N.Y. (last date accessed: 10 November 2009).

USAID, 2008. *Madagascar Food Security Programming Framework*, United States Agency for International Development, Washington, D.C., 57 p.

Vasudeva, G., 2003. Environmental conflict and agriculture intensification in India. *Food Security and Environmental Quality in the Developing World* (R. Lal, D. Hansen, N. Uphoff, and S. Slack, editors), Lewis Publishers, New York, N.Y., pp. 155-168.

Von Braun, Joachim, 1995. Employment for food security: Synthesis and policy conclusions, *Employment for Poverty Reduction and Food Security* (J. Von Braun, editor), International Food Policy Research Institute, Washington, D.C., pp. 303-319.

WFP Madagascar, 2006. *Madagascar: Comprehensive Food Security and Vulnerability Analysis (CFSVA),* United Nations World Food Programme, Rome, Italy, 95 p.

WHO, 2008. *The Global Food Crisis: Implications for the Health of People in the African Region*, World Health Organization (Regional Office for Africa), Brazzaville, Congo, 5 p.

Wong, D.S., and J. Lee, 2005. *Statistical Analysis of Geographic Information with ArcView GIS and ArcGIS,* John Wiley & Sons, Inc., Hoboken, New Jersey, 441 p.

Wright, P.C., 2007. The future of biodiversity in Madagascar: A view from Ranomafana National Park, *Natural Change and Human Impact in Madagascar* (S.M. Goodman and B.D. Patterson, editors), Smithsonian Institution Press, Washington, D.C., pp. 381-405.