

LAND COVER AND LANDSCAPE COMPOSITION CHANGE OF THE CAATINGA: A CASE  
STUDY FROM SÃO FRANCISCO VALLEY AREA

A Thesis  
by  
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## **Abstract**

### LAND COVER AND LANDSCAPE COMPOSITION CHANGE OF THE CAATINGA: A CASE STUDY FROM SÃO FRANCISCO VALLEY AREA

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Land use change impacts range from collective global climate effects to local degradation of ecosystem services available to humans. Consequently, understanding regional land use change has many ramifications. In northeastern Brazil, the caatinga, a semi-arid scrub vegetation rich in endemic species, has undergone extensive area loss and degradation due to increasing human populations, expansion of agriculture due to growth in irrigation, and recently infrastructure development for inter-basin transfer of water to support economic development. This research focuses on land use change of caatinga in Pernambuco State and North Central Bahia State along the São Francisco River. Landsat imagery from 1989 to 2008 is used to (1) detect the degree and direction of land use change, and (2) quantify changes in landscape structure, and (3) examine spatial variation in landscape structural changes. Change analysis highlights the loss of caatinga vegetation cover, especially along the São Francisco River where irrigation and urban cover expanded both along and

further away from the river. Transformation of landscape composition and structure varies from extensive coalescence of agriculture along the river, to increased spatial complexity and caatinga fragmentation (e.g., increased adjacency of caatinga and human land uses) further from the river, to spatially localized fragmentation of caatinga vegetation even further from the river.

Quantification of trends in spatial variation of landscape structure and composition provides a template for caatinga conservation, planning of ecosystem services, and evaluation of agricultural development impacts.

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A very special thanks to everyone who helped me in Brazil. They made this project possible. Finally, thank you to the Appalachian State Biology and Geography and Planning Departments, NASA Space Grant, CEMAFUNA, Federal Rural University of Pernambuco, and Federal University of the São Francisco Valley.

## **Dedication**

This thesis is dedicated to my family for their endless love and support.

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## **Chapter 1 – Introduction**

The surface of the Earth is in constant change. Cities expand, natural resources support human development, and forests are converted to agriculture. Approximately 41% of the Earth's surface has been altered (Sterling and Agnès 2008). Of all land cover classes, natural vegetation such as wetlands, forests, and grasslands are the most imperiled (Sterling and Agnès 2008). Because of the magnitude of loss and degradation, the impact of global land-cover change has been studied in connection with almost all of Earth's processes. Synthesis of important research efforts have revealed land use-land cover (LULC) change has altered the terrestrial water cycle (Sterling and Agnès 2008), driven climate change (Verburg et al. 2011), propelled biodiversity decline (Gerstner et al. 2014), and exacerbated the threat from pathogenic diseases (Estrada-Peña et al. 2014). Because of the role of land cover change in driving the greatest ecological and environmental issues, continuous and comprehensive monitoring and research of land use should be a priority for policymakers around the world.

Because of the complexity of LULC change on a global scale, a more general understanding of the LULC dynamics on a regional level will elucidate the most important impacts of change (Turner et al. 2007). In particular, studying areas experiencing rapid human development and agriculture expansion will provide insight to local and regional scale consequences for particular ecosystems and communities. The Brazilian caatinga is an impoverished area that has experienced both a high degree of change and a lack of LULC research (Ramos et al. 2008).

The caatinga is a semi-arid scrub forest situated in and exclusive to northeastern Brazil. This ecoregion is located within eight different Brazilian states and is confined by cerrado savanna to the west, Atlantic coastal forest to the east, and the tropical moist broadleaf forests of north-central Brazil. It has an estimated area of 844,453 km<sup>2</sup>, making it almost ten percent of the total area of Brazil (Instituto Brasileiro de Geografia e Estatística 2004). Caatinga, meaning “white forest” in the native language, Tupi, is most often characterized by small trees, thorny brush, arid grasses, and thorn scrub. Small-leaved, medium to tall, woody genera such as *Tabebuia* (Bignoniaceae), *Cavallinesia* (Bombacaceae), *Schinopsis* (Anacardiaceae), *Myracrodruon* (Anacardiaceae), and *Aspidoperma* (Apocynaceae) have historically dominated the ecoregion (Coimbra 1996). Recently, these woody forests have been largely destroyed for timber harvesting, farming, and ranching (De Melo and Catarina 2008). Today, typical genera include *Bromelia* (Bromeliaceae), *Pilosocereus* (Cactaceae), *Caesalpinia* (Caesalpiniaceae, Leguminosae), *Aspidoderma* (Apocynaceae), *Mimosa* (Mimosaceae, Leguminosae), and *Calliandra* (Fabaceae, Leguminosae). The tall caatinga forests, while existent in patches of nutrient rich soil, are becoming disproportionately scarce compared to shorter succulents, bromeliads, cacti, and spiny shrubs (Chappuis 2007).

Currently, less than 1% of the diverse biota of the caatinga is under protection (Leal et al. 2005). According to recent assessments there are over 900 species of vascular plants (Giulietti et al. 2004), 500 species of birds (Leal et al. 2003), 140 mammal species, and 230 fishes. Amongst these groups, endemism ranges between 3% in birds to 57% in fish (Rosa et al. 2003). Despite these assessments, the real number of species and the levels of endemism are potentially much greater. It is

estimated that over 41% of the region has never been surveyed by scientists and 80% of what has been surveyed was done poorly (Tabarelli et al. 2004).

Furthermore, addressing human poverty has been the political focus in the caatinga, and conservation is one of the lowest priorities despite potential links between biodiversity and human well-being (Leal et al. 2005). Serra das Capivara National Park, a popular ecotourist site located in Piaui State, is managed by the Brazilian Institute for the Environment and has strengthened the local economy in one of the caatinga's poorest regions. Because of the political climate, the need for scientific information is greater than ever; development has yet to acknowledge the declining biodiversity and ecological importance. The Nature Conservancy, World Bank, and the Global Environment Facility have responded with initiatives for scientific investigation. This includes 25 priority areas and an outline for a biodiversity corridor along the São Francisco River (Leal et al. 2005). Currently, none of these conservation projects have been implemented.

Likewise, despite its lack of notoriety, the ecoregion is important economically. More than 15% of the population of Brazil (the country has a population of 200 million) lives within the caatinga, despite only having 10% of the total area. The population is largely rural and extremely poor. Additionally, periodic long droughts, common in this area, greatly affect the viability of small scale agriculture. Water diversion projects have addressed the lack of water. Over the last century thousands of dams and reservoirs have been built to alleviate water related issues. Despite these efforts, desertification and drought are on the rise (Coimbra 1996). Many rivers, that once supported cattle transportation, are now seasonally dry due to extraction. Other rivers,

including the São Francisco River, have decreased water flow. A semi-distributed hydrologic model predicted that planned irrigation projects from the São Francisco River will divert more than  $140\text{m}^3\text{s}^{-1}$  of water (Maneta et al. 2009).

The caatinga is also characterized by its yearly rainfall. Average annual rainfall varies from 240mm in the most arid areas to 1500mm in the high Borborema Plateau (Giulietti et al. 2004). Most of this rainfall is concentrated within the months of March to July, while August to February is largely dry. These annual droughts have provided extreme challenges for modern agriculture and human habitation. Nonetheless, humans have caused changes to the landscape and natural vegetation resulting in habitat loss, degradation, and fragmentation.

Driving these land use changes are agriculture, commercial deforestation, and irrigation, all of which are unregulated and undermanaged. The majority of the caatinga's 25 million people lives in extreme poverty and depends on agriculture for subsistence (Leal et al. 2005). Because of the harsh conditions and lack of management options, slash and burn agriculture has become a common practice. This practice has converted much of the natural vegetation into temporary crop fields (Mamede and Araújo 2008). Although, timber extraction has decimated populations of many of the large woody trees that are of major ecological significance, other species are devastated by domesticated livestock because they lack resistance to intensive browsing. Overgrazing, by an estimated 10 million domesticated animals (Leal et al. 2005), forest exploitation, over tillage for agriculture, and slash and burn agriculture have led to extreme changes in land cover.

According to the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística 2011), 201,786 km<sup>2</sup> or 27.5% of the caatinga has already been transformed to agricultural and other types of intensive land uses. Through models that include roads, villages, and urban areas, the total habitat loss is estimated much higher than the number predicted by the IBGE (Leal et al. 2005). Given the lack of land management and conservation, the transformation of the caatinga landscape is likely to continue at an increasingly fast rate.

While the entire extent of the caatinga has experienced significant land use change, caatinga within Pernambuco and the São Francisco Valley serves as a good case study for land use change because of sharp urban and agriculture growth and the availability of ground collected land cover data. According to the Brazilian Institute of Geography and Statistics, the State of Pernambuco has the 8th largest livestock portfolio of Brazil and the second largest of Northeastern Brazil. In addition, the state is one of the largest sugar cane producers in Brazil (Instituto Brasileiro de Geografia e Estatística 2009). Other major agricultural products include banana, onion, corn, tomato, grape, and beans. The transition to agriculture, which has primarily occurred in the last 18 years, has likely caused major environmental changes. However, the amount of agriculture growth has yet to be quantified accurately. The southern border of Pernambuco, and the northern border of Bahia, is formed by the São Francisco River. Because of irrigation, major changes in land use have occurred near the river, but the extent of change and ecological impact has not been quantified.

The first objective of this study is to identify and map the land use changes that have occurred from 1989 to 2008 in the caatinga of Pernambuco. This time frame

covers a period of economic and population growth; the ecological effects of this growth are still uncertain. This will be carried out using a combination of ground data and satellite imagery. Although general regional trends over the timeframe of this study suggest a substantial increase of agriculture and urban areas and a decline of caatinga vegetation (Instituto Brasileiro de Geografia e Estatística 2009), an accurate, high-resolution analysis of change is necessary to characterize landscape composition change in the region.

As land cover changes, landscape structure also changes. Temporal changes of landscape structure are understudied. To address this need, my second objective is to quantify changes in landscape structure. Finally, because of variability in the landscape, particularly along the São Francisco River, the spatial variation in landscape structural changes was examined to determine how the study area has fragmented unevenly.

## **Chapter 2 - Methods**

### *Classification of Brazilian Caatinga*

The Brazilian Caatinga, located in northeastern Brazil, is a broad mosaic of different vegetation types. The caatinga is typically divided into eight different categories (Eiten 1983): caatinga forest, arborescent caatinga, arborescent-shrubby closed caatinga, arborescent-shrubby open caatinga, shrubby closed caatinga, shrubby open caatinga, caatinga savanna, and rocky caatinga savanna. Logging is likely to have made tall caatinga forests fragmented and scarce (Leal et al. 2005). The eight different types of caatinga were grouped into three land cover classes: dense shrubs, open shrubs, and caatinga forest. These three different vegetation types were used as training data of the land cover analysis.

### *Study Area*

The study area (fig. 1) is located in the Northeastern corner of the caatinga ecoregion, between 7°23'- 9°22' and 36°57'W- 40°31'W. This area includes portions of the states of Paraiba, Bahia, Ceara, and Alagoas but is primarily in the State of Pernambuco. This landscape was selected because it reflects large scale socioeconomic changes that have occurred throughout the caatinga. In addition, within the selected area, major new construction diverting water from the São Francisco River began in 2005. Financial support for long term research into the impacts of the São Francisco River Diversion Project was built into the project's plans. Recently, financial stress and concerns from different environmental and social movements have stalled some construction of the 650 kilometers of canal; this research project will provide baseline

**Fig. 1.** Map of Brazil showing the study area outlined in red



analyses of landscape composition and structure to define and document changes resulting from the manmade canals and reservoirs.

#### *Satellite Imagery*

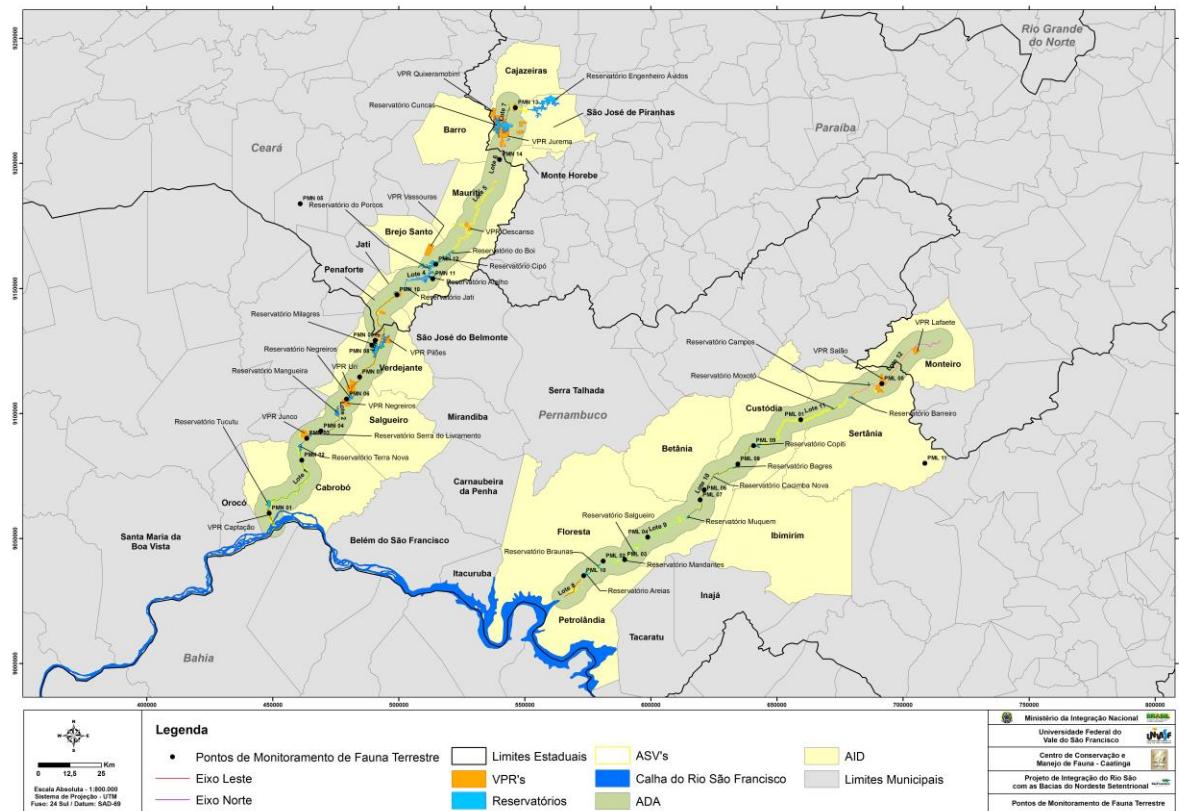
Land-cover patterns from Landsat 5 Thematic Mapper (TM) imagery were interpreted for two time periods, 1989 and 2008. The research area was encompassed by six different Landsat images for each time step. The twelve different images, mosaicked together to create two different time steps, all come from the height of the dry season (September, October, or November) which typically lasts June through December. To standardize climatic variations, all twelve images were taken between the months of September and November. For each time period, the six images all fell within a 50-day time period.

All Landsat data were downloaded from The United States Geological Survey, ortho-rectified, and geometrically corrected. The scenes were processed as “Level 1 Terrain Corrected (L1T)” data by the USGS. This L1T processing provides geometric, radiometric, and topographic accuracy using a combination of ground control points and a Digital Elevation Model and is considered, according to USGS’s level of processing, the best level of correction (Roy et al. 2010).

### *Training Data*

Training data (fig. 2) was derived from land cover maps developed by The Center of Conservation and Wildlife Management (Cemafauna Caatinga) and The Federal University of the São Francisco Valley (UNIVASF). The land cover maps were

**Fig. 2.** Map of the 25 research sites used for training data



created for 25 different, 2km radius, circular research sites located within the study area. For each site, extensive surveying for mammals, birds, plants, and fish were conducted over multiple years prior to 2008 by UNIVASF. Each map was classified using ResourceSat-1's LISS-3 sensor, surveying, and ground-truthing. Polygons were digitized and vegetation classified into three different types of caatinga (dense shrubs, open shrubs, and caatinga forest), agriculture, development and water. Because the study area is almost entirely agricultural and rural, an urban class was not included. Developed areas in the study area were predominantly mixed with agriculture, and were thus included in the agriculture land cover class.

#### *Pre-Processing*

In temporal change detection, the accuracy of the change analysis is proportional to the categorical accuracies of the input classified images. Therefore, refining satellite imagery to improve the accuracy of surface spectral reflectance is typically done prior to classification. There are typically two sets of errors that must be identified and corrected. Internal errors are produced by the remote sensing platform itself, and external errors are produced by variations in nature that occur over space and time. Internal errors are systematic and are generally identified and corrected with calibration measurements (Jensen 2005). Landsat 5 calibration parameters are applied by the USGS before distributing the imagery.

Variations between the different Landsat scenes of the same year were normalized during mosaicking. Mosaicking combined the multiple images into a single seamless composite image. While it is possible to mosaic unrectified images, the images were rectified to a standard map projection and datum (Jensen 2005). In ERDAS

Imagine, mosaics were done using Image Dodging, Color Balancing, and Feathering. In addition, cloud areas were excluded from the Image Dodging and Color Balancing processes, ensuring clouded pixels do not alter radiometric statistics during image mosaicking. An Exclude Areas tool in ERDAS Imagine excludes anomalous spots during pre-processing. These spots, if included, have the potential to skew the histogram of brightness values and thus affect the color balance of an image.

Image dodging was used to smooth color light imbalances over individual images, correcting for irregularities created by the Earth's surface. This includes hotspots and vignetting, two large types of imagery distortion. Image Dodging, done in ERDAS Imagine, calculates global statistics across a single image then applies a filter to smooth out imbalances in color across that single image. Secondly, color balancing was done to remove color variations across all the images. Because the images were from different dates by necessity, color balancing removed variations between the images while they were mosaicked together.

Feathering was used because the images overlapped and noticeable seams in the final mosaic were present. Feathering softens the edges of a seamlne by blending pixels within a certain distance. This blending used a linear interpolation and was distance weighted, for example, pixels further away from the seamlne were weighted less. This technique was applied to the geometric seamlines. All of these techniques were applied to the twelve images to produce two large images, one for each time period.

### *Classification*

Land cover information was obtained using a supervised classification. Based on climatic archives, the land cover classes were environmentally homogenous across the entire image, and the Cemafauna land cover maps were used to train the research area. Because the training data for each class were not assumed to be normally distributed, a nonparametric parallelepiped classification algorithm was used. This decision rule uses bounded regions of pixel values determined by the training data. The bounded regions of values were used to determine each pixel's membership. Using this particular algorithm, areas that do not fall within the determined region of values, or parallelepiped classes, are designated as unclassified. Similarly, pixels can fall into multiple classes. To rectify this limitation, pixels that were unclassified or were classified as multiple land cover classes, were subjected to an additional Maximum Likelihood Classifier. This classifier is based on probability, and calculates each pixel's probability of being in a particular class based on training data statistics. The pixel is assigned to the class of the highest probability.

### *Change Detection*

Change was detected by post-classification change detection (Jensen 2005). Images (classified using the same classification scheme) from 1989 and 2008 were compared pixel by pixel. The pixels that are the same, and the pixels that are different, between the two periods were tallied. This technique also provided information on the type of change, i.e to-from information.

### *Fragmentation Analysis*

Fragmentation analysis was done using Guido's Toolbox (Wade et al. 2003 and Ritters et al. 2012), a software package developed for raster image processing. The p23 metric was used to calculate fragmentation. This metric quantifies the proportion of adjacent pixels, in all cardinal directions, that contain the land cover of interest being fragmented by 'fragmenting pixels'. These 'fragmenting pixels' can be determined as 'interesting' or 'uninteresting' background pixels. Of the land cover classes, this study aimed to quantify caatinga fragmentation by agriculture. Water was determined to be an uninteresting background, and thus caatinga fragmentation did not take water pixels into account. The returned value, P, is the proportion of adjacent pixel pairs in cardinal directions that include at least one foreground pixel, for which the neighboring pixel is interesting background.

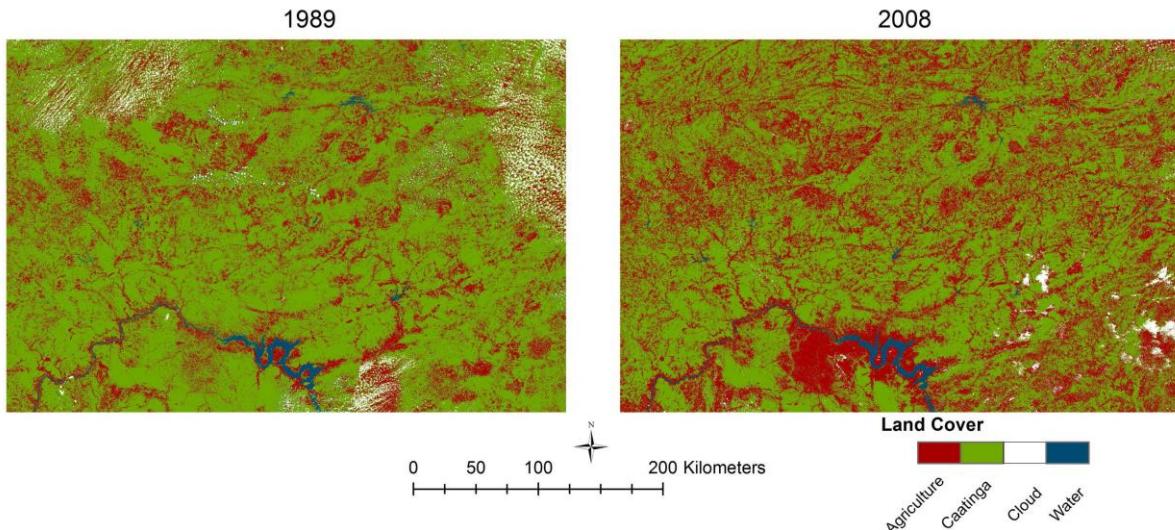
#### *Classification Accuracy Assessment*

Classification maps contain errors, and an accuracy assessment can measure the agreement between ground truthed data and classified images of unknown quality. User's accuracy (a measure of commission) and producer's accuracy (a measure of omission) were determined for the 2008 classified map using the available training data. Three hundred pixels, not used during classification, were selected at random from the training data and compared to the accompanying pixel of the classified map. User's accuracy was calculated by dividing the number of correctly identified pixels by the number determined in the classified map. Producer's accuracy was calculated by dividing the number of correctly identified pixels of a given class by the number of actual pixels of that class.

## Chapter 3 – Results

Over the study period, agriculture was greatly expanded while caatinga decreased in area. Agriculture expanded 13,330.6 km<sup>2</sup>, while caatinga lost 12,831.9 km<sup>2</sup>. In addition, the total amount of water cover decreased by 641 km<sup>2</sup>. Overall, 73,244.9 km<sup>2</sup> of land cover did not change between 1989 and 2008 (fig. 3).

**Fig. 3.** Land cover for the two years, 1989 and 2008, are shown after image processing and classification



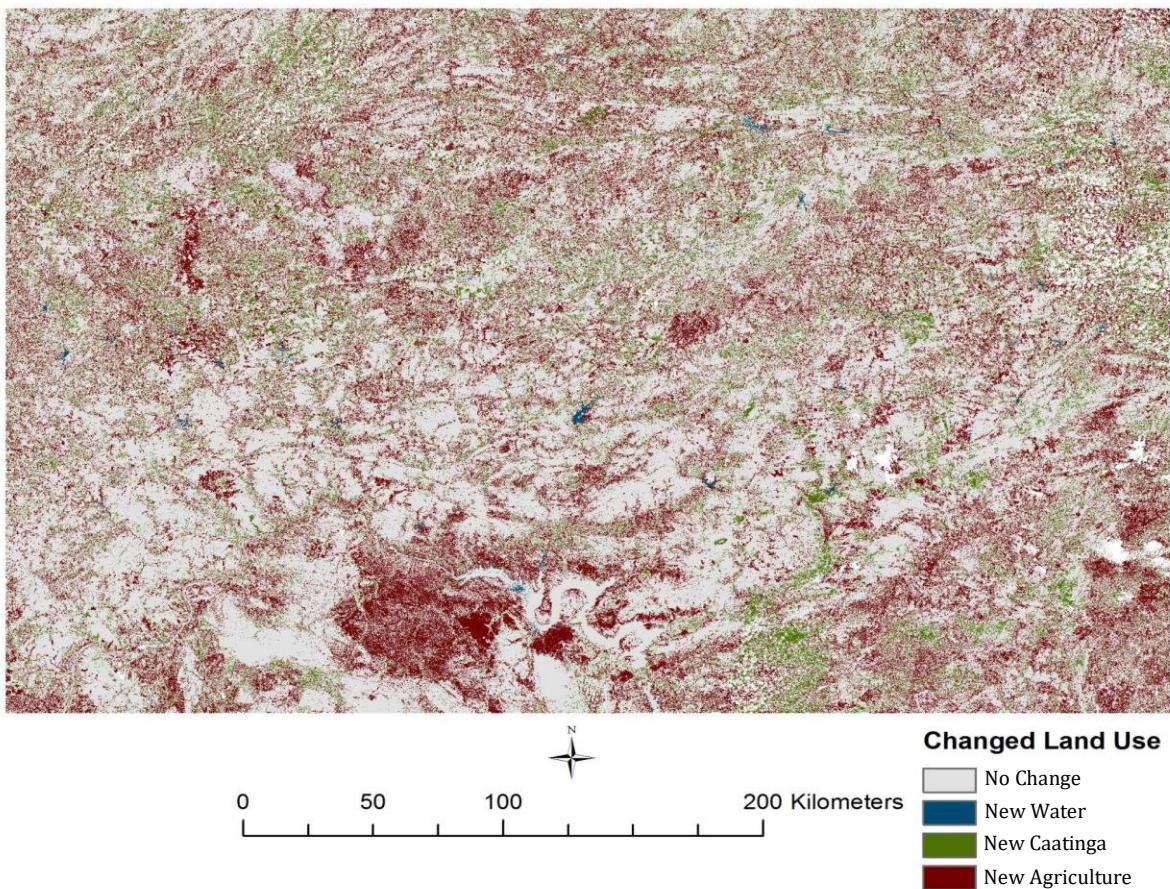
Spatially, the greatest change in land cover occurred around the São Francisco River (fig. 3 and 4 and Table 1). This was driven by the loss of caatinga and growth of agriculture. The heaviest concentration of agriculture growth along the river occurred at the city of Belem. At Belem, the river widens, and thus more water is available for irrigation. Bahia, the state south of the São Francisco River, saw the amount of agriculture grow the most. Agriculture expansion greatly increased the patch size and decreased the fragmentation. To a substantial, but slightly less degree, this trend continues along the São Francisco in both Pernambuco and Bahia.

Away from the river, agriculture expanded in a similar fashion. In 2008, agriculture had expanded from areas that were already such in 1989. However, these patches remain much smaller compared to the new, large agriculture dominated pixels close the river. While the total amount of caatinga decreased from 1989 to 2008, some areas experienced regrowth of caatinga. This did not occur in a geographic area, but happened in small amounts through the research area.

**Table 1.** The change matrix between land cover classes of the study area. The table compares the area ( $\text{km}^2$ ) of each land cover class between 1989 and 2008, for example there were 21335.1 $\text{km}^2$  of agriculture in 2008 that was Caatinga in 1989. The total land cover area for each year is also totaled.

Area( $\text{km}^2$ )		2008				<b>1989 Totals</b>	
		<i>Agriculture</i>	<i>Caatinga</i>	<i>Cloud</i>	<i>Water</i>		
<b>1989</b>	<i>Agriculture</i>	12940.9	8163.8	167.2	52.1	21324.1	
	<i>Caatinga</i>	21335.1	59267.9	573.8	202.7	81379.5	
	<i>Cloud</i>	179.1	412.7	5.5	13.0	610.4	
	<i>Water</i>	199.5	703.1	6.2	1030.5	1939.3	
		<b>2008 Totals</b>	34654.7	68547.6	752.7	1298.3	105253.3

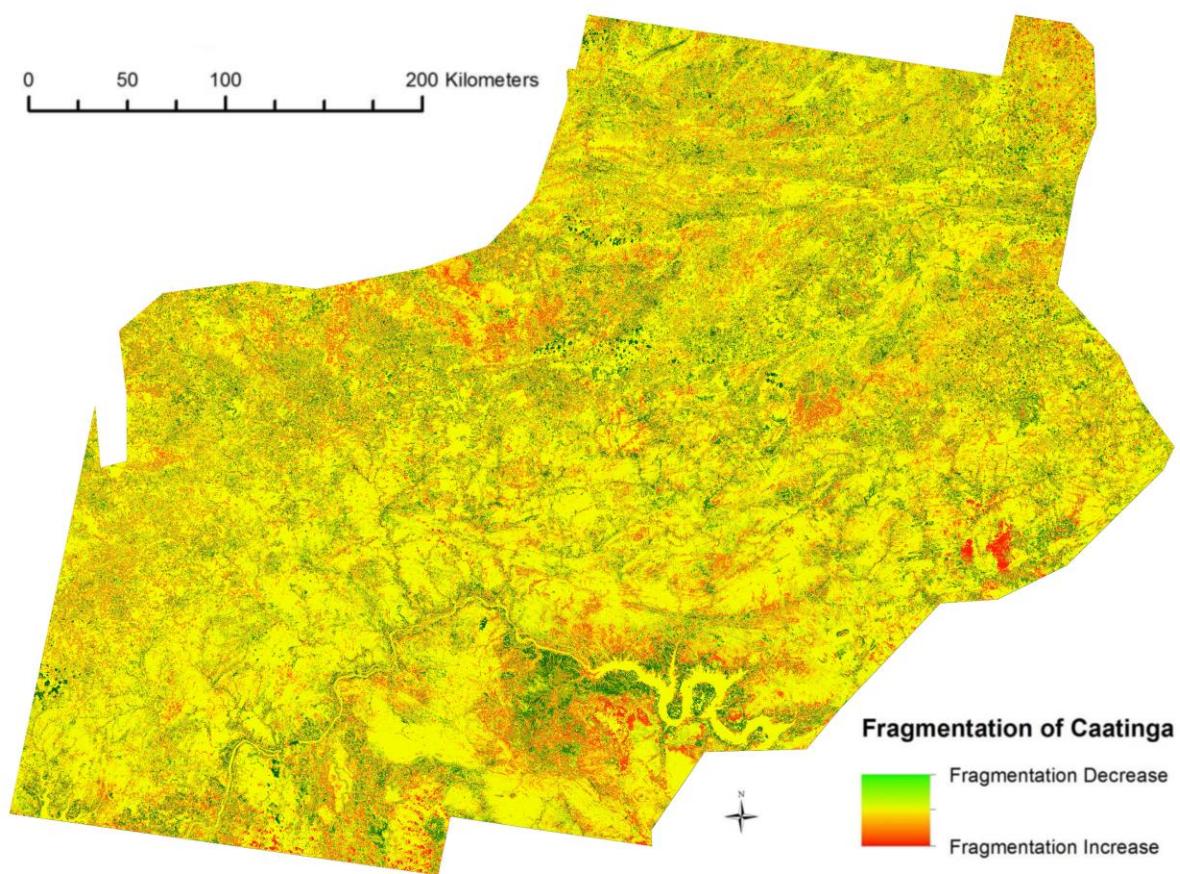
**Fig. 4.** Changes in land use are represented by their new land use in 2008.



Over the 19-year time study, there was a 72% increase in fragmentation of caatinga by agricultural expansion (Table 1). Increased irrigation agriculture along the São Francisco River (fig. 4 and Table 2) not only increased loss of caatinga, but also focused caatinga fragmentation surrounding that area (fig. 5). In Bahia, where agriculture expanded the greatest, caatinga fragmentation decreased. Because agriculture dominated the landscape, caatinga fragmentation was a minimum. Surrounding the areas of agriculture expansion and decreased fragmentation, caatinga fragmentation increased. As agriculture stretched further from the river, previous caatinga was being fragmented by the expanding new agriculture. Away from the river,

the pattern of change in fragmentation between 1989 and 2008 was similar to the pattern of land cover change. There was a mix of increased caatinga fragmentation and decreased caatinga fragmentation throughout the area, with an overall growth in fragmentation (fig. 5).

**Fig. 5.** A map of fragmentation, clipped to exclude areas skewed by cloud cover, depicts the fragmentation of caatinga by agriculture.



The accuracy assessment showed that the User's accuracy for the caatinga class was 87.2%, and its Producer's accuracy was 95% (Table 2). This demonstrates that 95.5% of the caatinga pixels in the ground truthed data were labeled correctly by the classification, while 87.2% of the caatinga pixels in the classified map were labeled correctly as determined by the ground truthed data. Of the agriculture and caatinga classes, the two classes focused on for further analysis, the Producer's accuracy for agriculture was notably lower. The low Producer's accuracy for this class suggests that my classification omitted agricultural pixels as compared to the reference data. Thus, the analyses will over underestimate the amount of caatinga fragmentation across the study area.

**Table 2.** The accuracy matrix, showing Producer's and User's accuracy for the four different land cover classes

		Classified Data				<b>Total</b>	<b>User's Accuracy</b>
		<i>Caatinga</i>	<i>Agriculture</i>	<i>Water</i>	<i>Cloud</i>		
<b>Training Data</b>	<i>Caatinga</i>	170	24	0	1	195	0.872
	<i>Agriculture</i>	8	82	0	1	91	0.901
	<i>Water</i>	0	0	5	1	6	0.833
	<i>Cloud</i>	0	2	0	6	8	0.750
	<b>Total</b>	178	108	5	9		
<b>Producer's Accuracy</b>		0.955	0.759	1	0.667		

## **Chapter 4 – Discussion**

### *Expansion of Agriculture*

The economy of Pernambuco, Brazil, is based on animal husbandry and agriculture, historically small farms. Today's demand for food and herbal medicine has been matched by an increase in production. The increase of food demand and production is well documented by the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística 2009). Studies have shown that the increase in food production has expanded primarily into formerly forested land. (Lapola et al. 2010), and land has been changed by new large-scale plantations made possible by irrigation (Beuchle et al. 2015). The scale of land cover change caused by agricultural expansion has been unknown, but predicted to be growing intensively with large ecological impacts (Beuchle et al. 2015).

These presumed economic and ecological trends are quantified by the landscape change analysis. Along the São Francisco River land cover changed greatly from caatinga to agriculture. Agriculture coalesced to larger patches as it began to dominate the landscape. Overall fragmentation decreased as the loss of caatinga gave way to new agriculture. Similarly, the clear majority of agriculture near the river is expansion of preexisting agriculture as opposed to new patches. Because most of the crops grown in this area require plentiful water for irrigation, the change near the river is primarily fruit and vegetable expansion.

The expansion of agriculture further away from the São Francisco River is less likely to be from new agribusiness farms. Studies have shown that over the study

period farms have grown from small units to larger, subcontracted farms (Helfand 2004). While this could be happening further away from the river on a smaller scale, most of the farms are still small (Instituto Brasileiro de Geografia e Estatística 2009). In 2008, most of the agriculture patches away from the river stayed relatively small, similar to the new caatinga patches (fig. 3 and 4). The lack of larger patches, agriculture land cover growth, and clear geographic pattern speaks to the nature of small farms deep in the caatinga. The farms, and particularly livestock, are largely unconfined and graze and grow without boundary. Because the farms and pastures are unconfined, and tend to be a mixture of agriculture and caatinga, the pixels could be fluctuating between land cover classes. Additionally, unconfined farm animals could prevent new caatinga from ever fully regenerating, even though the land is not agricultural either. Despite this, it should be noted that the study area as whole saw an increase in agriculture and loss of caatinga.

It should also be noted that man-made reservoirs are scattered throughout the landscape and further support small farm agriculture. Expanding farms, to meet the growing demand of fruit and vegetable growth, could explain the expansion of some agriculture further from the main São Francisco River water source.

#### *Loss of Water*

The flow of the São Francisco River decreased over the study time frame (Maneta 2009). Furthermore, certain reaches (upstream of the research area) are at risk of completely drying. Thus, some of the decrease in water land cover is potentially due to a long-term decrease in the flow of the river. The resolution of my results do not show a dramatic decrease in the width of the river. Higher spatial resolution analysis

and changes in river depth and width would be needed to determine the loss of São Francisco River land cover.

It should also be noted that many watercourses of Pernambuco, exclusive of the São Francisco River, are intermittent streams and reservoirs (Maltchick 2006). During the rainy season, runoff water and ground flow will fill the rivers and streams in the region. Rainfall, recorded at Petrolina (located in the southwest of the research area), was high in 1989 at 893.3mm according to the Food and Agriculture Organization's report in 2000 (Rada and Valdes 2012). In contrast, the average annual rainfall is close to 500mm (Leal et al. 2005). The change in water land cover is likely due to variations in precipitation during the months leading up to the time frame. Supporting this are several new large reservoirs located deep in the caatinga (fig. 3 and 4).

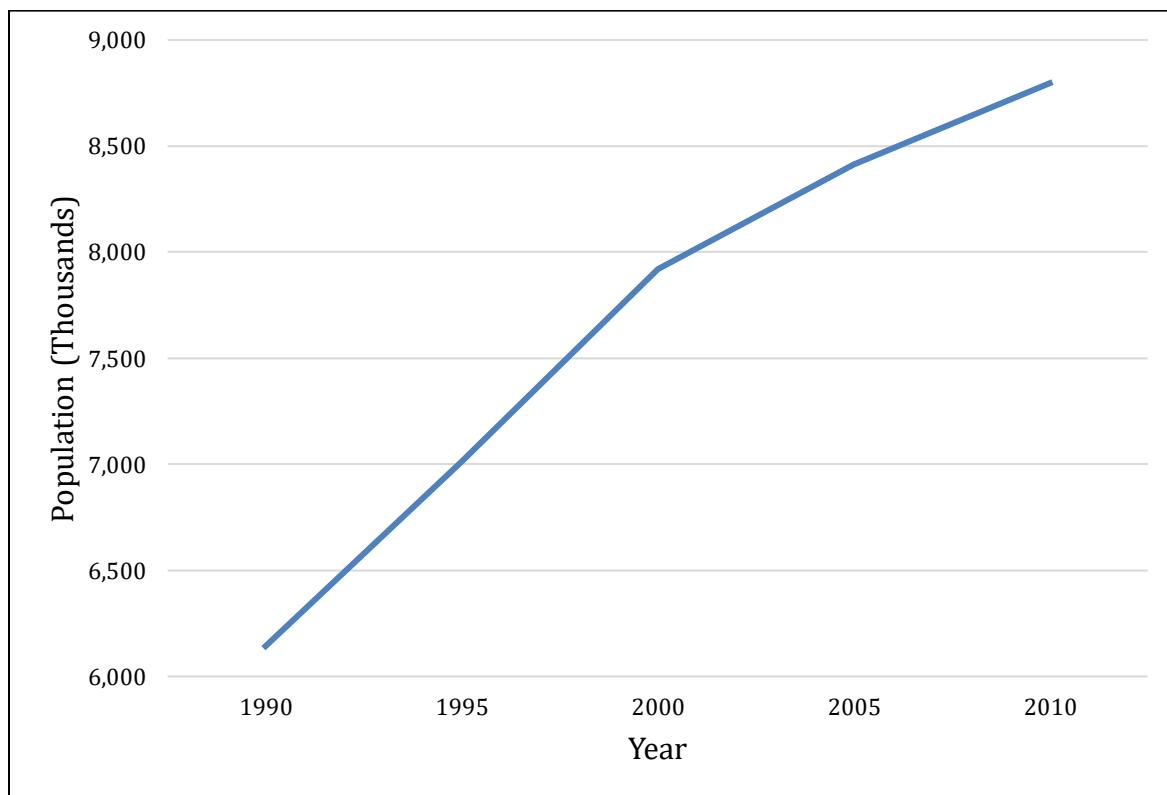
#### *Population and Economic Growth*

The State of Pernambuco has grown continuously for the last fifty years (Instituto Brasileiro de Geografia e Estatística 2011). The population growth in the largest city within the study area, Petrolina, has grown at a rate of 3.2% (fig. 6; Instituto Brasileiro de Geografia e Estatística 2005). Between 1991 and 2000, the entire State of Pernambuco, which makes up the majority of the study area, grew at a rate of 1.2% (Instituto Brasileiro de Geografia e Estatística 2005). The population growth prior to that decade was faster.

Human population growth is correlated with land cover change (Meyer and Turner 1994). The correlation between the population growth and rate of change of land use has been studied, but few conclusions have been made; most highlight the complexity of land cover change as the hypothesized driver of change (Meyer and

Turner 1994). However, the unique development of the caatinga and its well documented agriculture expansion point to population growth being positively associated with land cover change.

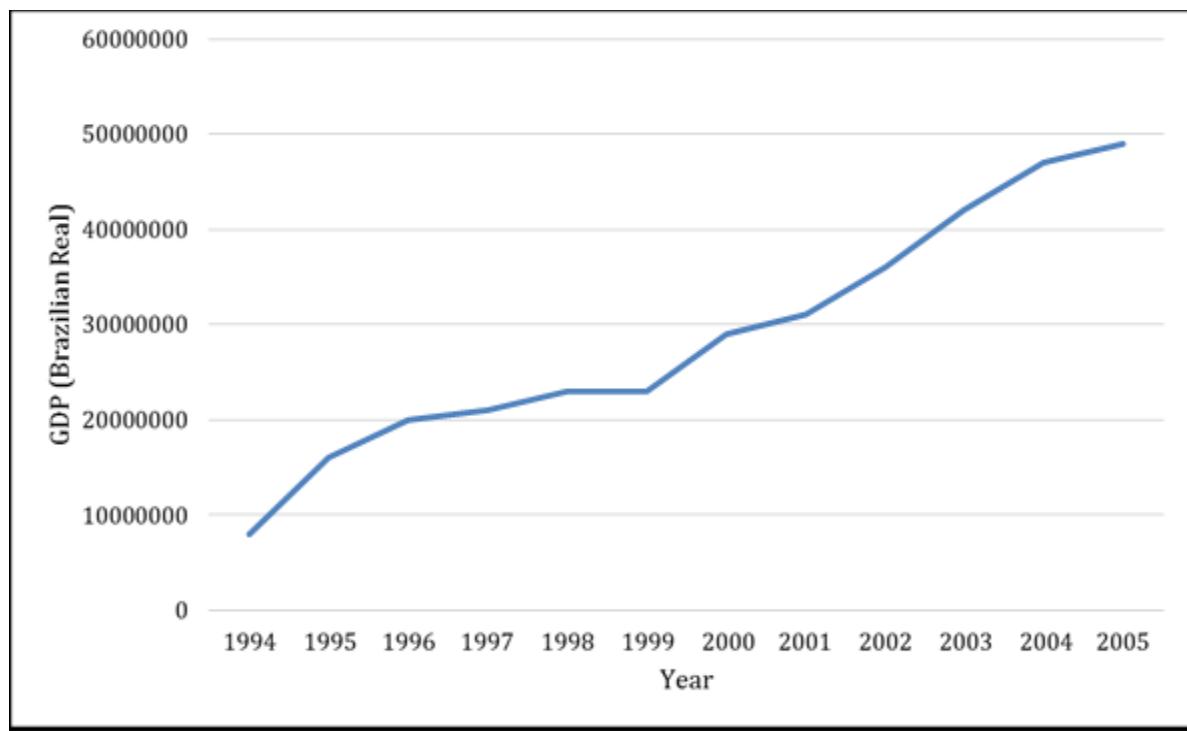
**Fig. 6.** Population growth of Pernambuco between 1990 and 2010.



Furthermore, several studies cite increased economic opportunities as one of the major underlying drivers of land cover changes (Baer 2001). Therefore, the growth in economy, in conjunction with population, could relate with the changes in land cover as land is necessary for agriculture and production. The economy of Pernambuco, based on agriculture and animal husbandry, has been growing rapidly during the time frame of the study (fig. 7; Instituto Brasileiro de Geografia e Estatística 2003). The GDP of the state grew more than 40% between 1989 and 2008. Further studies closely examining

industry and land cover change could expound on the underlying factors of land cover change in the state. With agriculture and animal husbandry as the largest industries, Pernambuco seems aligned with global trends where these industries are large contributors to land cover change globally (Lambin et al. 2001).

**Fig. 7.** GDP by year of Petrolina. The graph and the data were produced by the Brazilian Institute of Geography and Statistics.

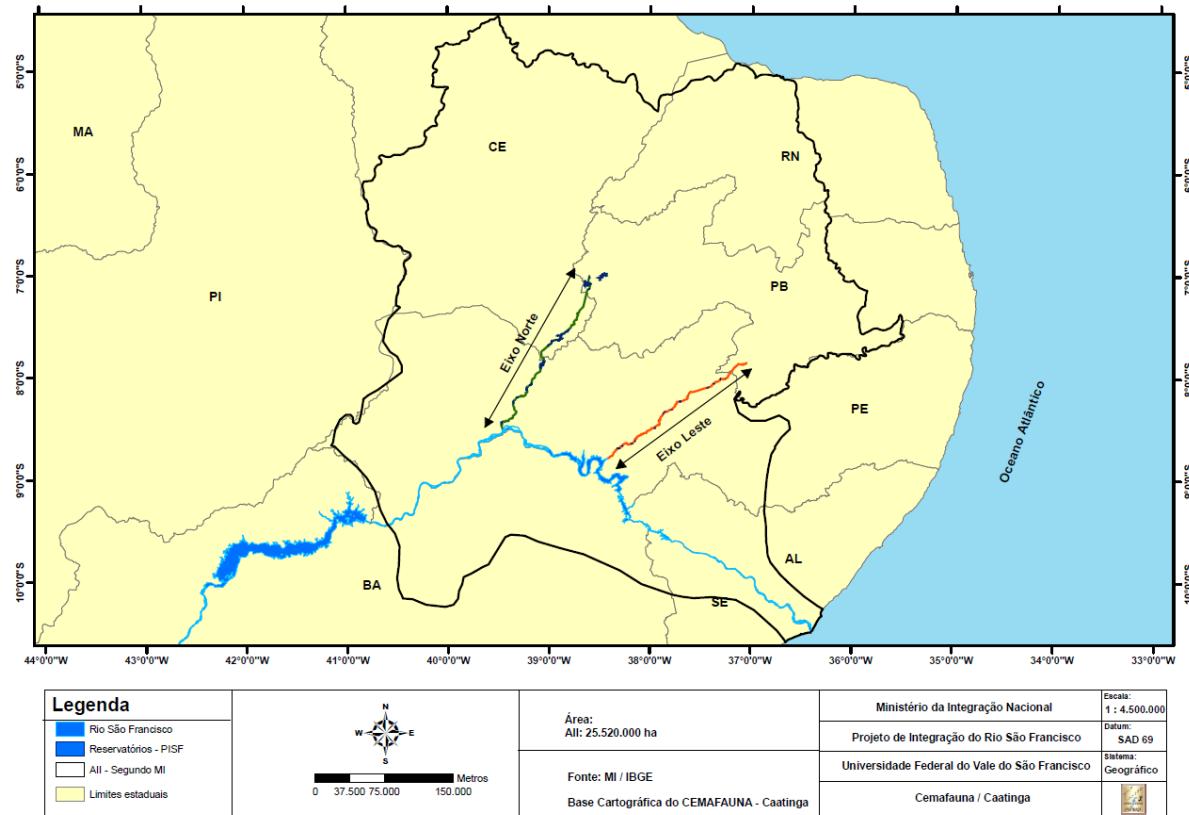


#### *Controversial Diversion Project*

In 2005, a water diversion project was proposed to pump water from the São Francisco River north. The project is designed to bring irrigation water to the arid areas of Pernambuco and further north. Following environmental and economic concerns, the project has been contested and reexamined, but has continued. Construction, which started in 2009, is scheduled to be complete by 2025 and cost the

Brazilian government more than 12 million dollars. Incidentally, agriculture growth showed the greatest concentration around the canals that were built before the study ended (fig. 8).

**Fig. 8.** Map of the proposed water diversion project.



However, water wasn't being used for irrigation at this point. Agriculture growth was therefore unrelated to the canals, and more likely driven by the proximity the São Francisco River, the largest body of water in Pernambuco. Given the need for irrigation water and economic expansion of agriculture, land use change in the study area is likely to occur even more rapidly in the next several decades as the canals bring water north and promote mostly larger agricultural patches. It is likely that the irrigation will benefit large scale farms and the landscape will transfer to large unfragmented

agriculture patches interspersed with some small patches of caatinga. This study can thus serve as a base line to not only land cover changes in the future, but also as a comparison of rates of land cover change as the water relocation project is complete.

## **Chapter 5 – Applications**

Land use change results reveal a complex mosaic of increasing and decreasing caatinga throughout the study area, with loss of caatinga and increased fragmentation of caatinga concentrated along the São Francisco River. Field observations indicate this is likely due to expansion of irrigation and abandonment of marginal unirrigated agriculture. The new, early successional caatinga arose diffusely over the study area by abandonment of degraded agricultural land, but generally occurred further from the river. Patterns of land cover change distant from the river reveal isolated small acres of increased water storage capacity surrounded by new irrigated agriculture. Despite this spatial variation, fragmentation analysis revealed an overall 72% increase in caatinga fragmentation. Significant impacts on biodiversity and ecosystem functioning are thus likely to expand in this imperiled ecoregion.

Anthropogenic land use change has many impacts, including the potential to drive the emergence of infectious disease (Patz et al. 2004, Foley et al. 2005, and Jones et al. 2008). Irrigation, deforestation, agricultural expansion, or expanding urban environments can modify how diseases are transmitted by causing a cascade of factors (for example poverty, pollution, habitat formation, migration, and disease vector/pathogen habitat) that exacerbate spread. These are complex issues that have been understudied for most diseases (Patz et al. 2004). American visceral leishmaniasis is considered by the Brazilian Ministry of Health to be one of the most severe public health problems in the country (Costa 2008). American visceral leishmaniasis is quickly reemerging in the rural caatinga of the Brazilian Northeast and has spread rapidly in urban and agricultural areas. Case studies (Lambin et al. 2001;

Hartemink et al. 2011) have identified the hosts and vectors of visceral leishmaniasis and expansion of irrigation and agriculture have been hypothesized to expand habitat for both. Nonetheless, little detail is known about the interactions between the vectors, reservoirs, and land use change along the São Francisco River. Consequently, this research can serve as a template to document on going land use changes relative to future disease outbreaks and the distribution of human visceral leishmaniasis.

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## **Vita**

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