FOREST CONNECTIVITY FROM A BIRD'S EYE VIEW: LINKING CLOUD FORESTS TO MANGROVES IN THE BELLBIRD BIOLOGICAL CORRIDOR OF COSTA RICA

by

STEVE PADGETT VASQUEZ

(Under the Direction of Marguerite Madden)

ABSTRACT

The Bellbird Biological Corridor, known in Spanish as the Corredor Biológico Pájaro Campana (CBPC), is a designated conservation area in Costa Rica that aims to bridge the cloud forests of the central mountainous Monteverde region with the coastal mangroves in the Gulf of Nicoya. The CBPC is not a true corridor since it does not provide connected, linear land between the cloud forests and the mangroves. In March of 2011, the CBPC Initiative published a 5-year strategic plan and identified the need to develop a baseline study of forest distribution and connectivity within the CBPC in order to identify and prioritize reforestation, restoration, and conservation projects. This dissertation uses remotely sensed data and geospatial analyses to examine broad-scale spatial and temporal changes in the Costa Rican CBPC landscape related to multiple perspectives of land stewardship and use. Specifically, land cover/land use derived from a time-series of satellite imagery was coupled with information on national conservation policy decisions, ecosystem services and stakeholder concerns to: 1) track longitudinal changes in forest cover to assess forest connectivity over a broad area between 1974 and 2014; 2) evaluate the spatial distribution of the Payment for Ecosystem Services Contracts within the corridor; and 3) identify key areas for future conservation that balance human needs and ecosystem values. The aim of these efforts is to further our understanding of the impacts of conservation policies and practices on critical ecosystem processes such as biodiversity. Results of this investigation are expected to promote forest connectivity and help turn the CBPC from a designated conservation area into a functional wildlife corridor.

INDEX WORDS: Landsat, Forest Cover Change, Wide Dynamic Vegetation Index, Linkage Mapper, Corridor Modeling, Circuit Theory, Payment for Environmental Services, Costa Rica, Corredor Biológico Pájaro Campana, Bellbird Biological Corridor, UGA Costa Rica Campus

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DEDICATION

I wish to dedicate my dissertation to Lauren Childs-Gleason and Jamie Favors who help make the world a better place with every project and who inspire me to follow in their footsteps.

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How far back should I go to give thanks to those who have helped me along this long academic process? I am not sure, so I will start by thanking my committee. Dr. Marguerite Madden is the reason why I decided to join UGA and she became my mentor even before the first day of class. Despite having a busy travel schedule and many graduate students, she always managed to make time for all of us. It has been a real treat to be part of her Center for Geospatial Research (CGR). Dr. Quint Newcomer was a source of local knowledge and a great facilitator in meeting local stakeholders in Costa Rica. Starting work in a new country and region was a bit intimidating, but Quint helped make all the right introductions to ensure my work had meaningful impact, while being the best personal guide anyone could hope for! I never quite knew what it was to be Latino until I started living in the U.S. However, it wasn't until I met Dr. Fausto Sarmiento that came to learn and appreciate the diverse history and culture of Latin American. Thanks to Fausto, I now have a better understanding of who I am. Dr. Deepak Mishra is a walking encyclopedia when it comes to remote sensing. It wasn't until I started taking his class that I realized how little I knew about the topic. Lucky for me, Deepak is also one of the funniest professors I have ever had. Thank you for sharing your knowledge! Dr. Nate Nibbelink is the reason why I even considered Costa Rica as my study site for my research. Nate gave me an opportunity to visit the UGA Costa Rica campus and I never looked back.

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INTRODUCTION AND BACKGROUND INFORMATION

Introduction

Declining forest cover, leading to forest fragmentation and habitat loss, contributes to the interrelated and global environmental threats of climate change (Kalnay & Cai, 2003), loss of biodiversity (Turner et al., 2007), and decreased environmental services (Vitousek et al., 1997). This triple threat has led to an increased interest in biological corridors since wildlife linkages can help reduce the effects of habitat fragmentation on local fauna and flora (Beier & Noss, 1998; Damschen et al., 2006). A biological corridor is a swath of connected, linear land areas joining habitats that facilitate animal movement (Beier et al., 2008; Singleton & McRae, 2013). Additionally, corridors help plant dispersal and retain more native plant species than isolated patches while not promoting the invasion of exotic species, making them a great tool for biodiversity conservation (Damschen et al., 2006).

Central America's forest was cleared at an alarming rate from the 1950s through the 1980s (Myers & Tucker, 1987), due in part to the expanding cattle industry that converted forests into pasture (Kaimowitz, 1996). In Costa Rica, two thirds of the country's tropical forests were cleared during this period (Guindon, 1996). To help promote biodiversity conservation and reforestation, a network of reserves covering 12% of Costa Rica's land areas was created (Sánchez-Azofeifa et al., 2003). In order to better link these protected areas and to increase habitat for migratory species or species that require larger home ranges, 37 corridors were established across the country (SINAC, 2009). El Corredor Biológico Pájaro Campana (CBPC) of Costa Rica, known in English as the Bellbird Biological Corridor, is one of those designated conservation areas, encompassing a 664 square kilometer swath extending from the continental divide to the western coast of Costa Rica. Connectivity conservation planning has traditionally relied on a focal species approach, which builds upon the concept of the umbrella species, like a top predator or endangered species, whose requirements are believed to include the needs of other species (Lambeck, 1997). The namesake of the CBPC is the threatened Three-Wattled Bellbird (*Procnias tricarunculatus*), one of Central America's largest frugivores with the most complex migratory pattern recorded for a tropical species (Powell & Bjork, 2004).

Landscape connectivity is the degree to which movement of organisms is facilitated or impeded among source patches (Forman & Godron, 1986; Taylor et al., 1993). Despite there being a consensus on the importance of landscape connectivity (Hilty et al., 2012), there is still much debate about how connectivity along the landscape should be modeled and managed (Beier et al., 2008; Kindlmann & Burel, 2008). A successful corridor design typically relies on both the structural connectivity (characteristics of the landscape) and its functional connectivity (aspects affecting mobility of the species) (Adriaensen et al., 2003). Even though the CBPC is a designated conservation area, it is not a purely intact corridor since it is a mosaic of protected and unprotected areas including large and small-scale agriculture, roads and towns. Maintaining and improving forest connectivity in the CBPC is especially important due to forest conversion to agricultural lands and non-forested areas with lower species richness (Daily et al., 2003).

This dissertation uses remotely sensed data and geospatial analyses to examine broad-scale spatial and temporal changes in the Costa Rican CBPC landscape related to multiple perspectives of land stewardship and use. Specifically, land cover/land use derived from a time-series of satellite imagery was coupled with information on national conservation policy decisions, ecosystem services and stakeholder concerns to: 1) track longitudinal changes in forest cover to assess forest connectivity over a broad area; 2) evaluate the spatial distribution of the Payment for Ecosystem Services Contracts within the corridor; and 3) identify key areas for future conservation that balance human needs and ecosystem values. The aim of these efforts is to further our understanding of the impacts of conservation policies and practices on critical ecosystem processes such as biodiversity. Results of this investigation are expected to promote forest connectivity and help turn the CBPC from a designated conservation area into a functional wildlife corridor.

How ICON Influenced My Research

I started pursuing my Ph.D. in Integrative Conservation (ICON) and Geography in Fall of 2012. I was coming into the program with a background in applied remote sensing and geographic information system (GIS) and was eager to learn on how I could make my research more holistic and inclusive. One of the first lessons I learned from ICON was that, in essence, environmental issues fall in the realm of political ecology. I understand political ecology to be the study of the relationships between the environment and changes in the environment with political, economic, and social factors. I also see political ecology as a spectrum where on one side you can focus more on the political than the ecology and on the other side you have the opposite, where you focus more on the ecology than the political. Regardless of where your research falls in the spectrum, one of the goals of political ecology is engagement between the political (economic, social, etc.) and the ecological.

I first traveled to the CBPC in April of 2013 and met with representatives from the different stakeholders that make up the CBPC Council in order to get an idea of the ongoing research and the research needs within the corridor. I wanted to avoid duplicating another person’s research. More importantly, by engaging with local stakeholders I could frame my research in a meaningful way and also increase the impact of any resulting study. The CBPC Initiative was established in 2007 and is composed of a variety of private reserves, rural communities, research and environmental institutions, private companies, governmental agencies, educational institutions, among others. Their mission is to reestablish and maintain biological connectivity, the conservation of natural resources, and the well- being of local communities (Welch et al., 2011). In March of 2011, the CBPC Initiative published a 5-year strategic plan. In addition to highlighting current partners, a legal framework, and a timetable, it also identified several goals including the need to assess the current state of forest connectivity, water resources, biodiversity, and other biophysical conditions in the CBPC. An assessment of forest connectivity and current land use within the CBPC is needed in order to identify and prioritize important areas for conservation action including reforestation, restoration and protection. The CBPC Initiative has identified the need for this research, but currently lacks human resources and expertise to accomplish the work.

I also worked with the University of Georgia Costa Rica Campus (UGA-CR) in regards to their CBPC conservation efforts. In 2008, UGA-CR began a reforestation program with the goal to increase forest cover within the CBPC. In the first three years of the program, over 28,000 native trees were planted in areas, mostly privately-owned farms, near the campus (Cox, Newcomer, & Strawser, 2014). The UGA-CR plans to expand their reforestation program and could improve their efforts toward meeting broad regional conservation goals by implementing targeted reforestation efforts. A remote sensing and GIS land use land cover change assessment tool developed in this dissertation research offers UGA-CR a decision support to help advance this program.

As I met with the local stakeholders, there were several concerns that kept being brought up. Many felt that even though there was scientific research being conducted in the corridor, the data and results were not being shared. Several used the term "helicopter research" to describe the act of researchers who traveled to the CBPC and once their research was completed, would leave with their data and not return. In some cases, the research would be published in a journal, which may or may not be easily accessible of freely available to the public. Another point that was brought up was the need to have GIS data easily accessible to facilitate research. I personally gave the Monteverde Institute a copy of the 2008 Digital Atlas of Costa Rica. In 2013, the Monteverde Institute began to collect GIS data of the region and were having a hard time getting a copy of the Digital Atlas, even though the geodatabase is intended to be freely available. A year later I gave them the updated 2014 Digital Atlas of Costa Rica along with the National Forest Map produced by the German Federal Enterprise for International Cooperation, known in German as the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). This experience made a great impression on me and influenced how I framed my research. This experience greatly influenced the framework of my research and emphasized the importance of local communication and mutual respect in conducting international research. It also motivated me to find a way to increase access to Costa Rican GIS data, along with the data and methodology that I would develop in order to ensure that the research results would be useful and valued by those who can benefit from it.

Research Objectives

Following the Introductory Chapter of this dissertation, the overall goal of Chapter 2 is to create a baseline of forest cover within the CPBC and conduct a time-series analysis to quantify trends in long-term land use/land cover (LULC) changes over a 40-year period, 1974 to 2014. This research also created a methodology that can be used by policy makers to update LULC conditions by analyzing NASA satellite imagery and tracking forest changes over time. There have been nation-wide (SINAC & REDD-CCAD-GIZ, 2015) and local (Chinchilla Ramos, 2015) studies looking at forest cover by using European RapidEye satellite imagery from 2012. However, replicating and updating these studies are cost prohibitive to local stakeholders since RapidEye imagery is not freely available. There have also been nation-wide studies tracking forest cover change in Costa Rica (Joyce, 2006; Sánchez-Azofeifa et al., 2001) using freely available NASA satellite imagery, but none specifically tracking forest cover in the CBPC or providing the results and data to local policy makers.

In the mid 1990's Costa Rica established its Payment for Environmental Services (PES), known in Spanish as Pago por Servicios Ambientales (PSA). Determining the effectiveness of the PES program has proven difficult. Previous studies in Costa Rica claim that improving the spatial targeting, in other words, the intentional geographic distribution, of PES contracts would improve the effectiveness of the PES contracts (Robalino & Pfaff, 2013; Wünscher et al., 2008). The goal of Chapter 3 is to evaluate the spatial targeting of the PES contracts that were awarded within the CBPC between 2008 and 2012. In an attempt to evaluate the program holistically, Allen and Padgett-Vasquez (2017) combined remote sensing, GIS, along with interviews and ethnography to untangle the relationship between national policy, forest regrowth, and social-ecological sustainability.

The CBPC is a designated conservation area. However, some areas within CBPC are more ecologically relevant than others and have a bigger impact in terms of ecosystem services they provide. The overall goal of Chapter 4 is to identify key conservation areas that promote forest connectivity based on corridor modeling and identify least cost paths between forests. Since both the amount of the forest that remains and its distribution influence the conservation value of the area (Daily et al., 2003), it is important to identify those key areas. Fagen et al. (2016) showed that reforestation of priority areas in the San Juan-La Selva Biological Corridor, which is located in the Northeastern region of Costa Rica, would lead to increased forest connectivity and enhance the connectivity benefits of reforestation. Developing data and assessing the ecological value of lands connecting existing conservation areas will contribute to future tools for determining priority areas for reforestation and conservation efforts in the CPBC. This will, in turn, benefit local conservation efforts, including the reforestation program at the UGA Costa Rica Campus, located in the San Luis Valley within the CBPC.

In Chapter 5, we explored the use of circuit theory to model functional connectivity across the CPBC. We adapted a methodology developed by Koen et al (2014) that did not require independent, field-collected data, which are often not readily available. Additionally, the method is not sensitive to the placement of nodes for connectivity estimation and did not rely on a focal species, such as the Three-Wattled Bellbird. When then used the results to evaluate the placement of PES contracts within the CBPC.

In Chapter 6 the contributions of this dissertation research are summarized and future investigations are proposed, along with exploring the broader significance of the research. Apart from the benefits provided by products and results of this study, the CBPC will be able to build upon the generated data and methodology for future efforts to create decision support tools aiding the conservation efforts of the CBPC Initiative. The geospatial data, along with video tutorials created in this research to convey how to replicate these studies, are available at http://www.stevepadgettvasquez.com/ facilitating the capacity of local stakeholders within the CBPC to update or customize this research.

Study Area

The CBPC is described in Spanish as a *puente de vida*, "a bridge of life", since it connects the mountainous Monteverde Cloud Forest Reserve at the continental divide to the coastal mangrove forest of the Gulf of Nicoya. The CBPC, covering approximately 66,400 hectares is delineated by the watersheds of the Aranjuez, Guacimal, and Lagartos Rivers (Figure 1.1). It is extremely rich in biodiversity, providing habitat to nearly half of all faunal species in Costa Rica, including 47% of the reptilian species, 51% of avian species, and 48% of mammalian species. (Welch et al., 2011). There are 12 distinct Holdridge life zones, or vegetation types, in Costa Rica (Holdridge, 1979) and 11 of those life zones can be found within the CBPC (Haber et al., 2000).

The CBPC includes intact and protected cloud forest areas such as the popular tourist destination of the Monteverde Cloud Forest Reserve with the highest elevation at 1,846 m (Burlingame, 2000). Moving down the elevation gradient to about 1,300 m, premontane forests become more mixed and fragmented as agriculture becomes more common. At higher elevations, fine-scale agricultural farms are common, where landowners rely on cattle and dairy production, coffee farming, tourism, and some subsistence agriculture with an average farm size of 30ha (Allen & Padgett Vásquez, 2017). At the lower elevations of approximately 250 m, broad-scale industrial agriculture of pineapple and sugar cane plantations dominate the landscape, a trend that has increased in the last twenty years (Fagan et al., 2013). At the lowest elevations near sea level, mangrove forest providing rich habitat for fish and shellfish can be found along the Gulf of Nicoya. The protected areas within the CBPC are both government and privately owned and are found at the highest elevations in the cloud forest (above 1400 m) and the lowest elevations along the mangroves (just above sea level). The middle elevation areas are particularly underrepresented nationwide in Costa Rica's biological reserves (Powell et al., 2000).

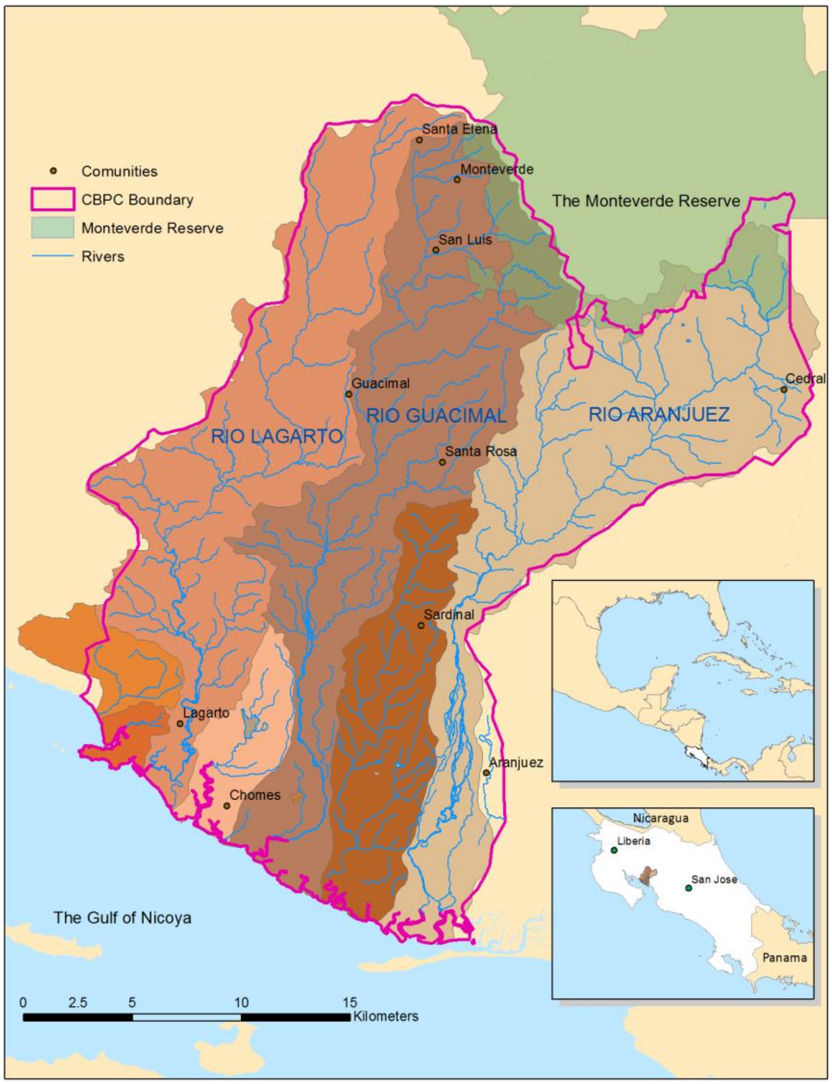

Figure 1.1 Study Area: Corredor Biológico Pájaro Campana and its main watersheds

Background

Historical Perspective of Conservation in Costa Rica

Mesoamerica is one of 25 biodiversity hotspots around the world (N. Myers, Mittermeier, Mittermeier, Da Fonseca, & Kent, 2000). Despite its size being smaller than the state of West Virginia, Costa Rica is home to more than 4% of described species in the world (Obando, 2007) and is sometimes described as the world's laboratory for tropical conservation (Boza et al., 1995). However, Costa Rica did not always have environmentally friendly policies and regulation, which can be seen in how much its forest cover has fluctuated in the last 50 years. In 1941, Costa Rica passed a law that permitted possession of up to 300 hectares of uninhabited public land if the occupant cleared more than half of it and maintained at least one cow for every 5 hectares (Brockett & Gottfried, 2002). Land ownership was established by "improving the land," which often meant converting forest to crops or pasture. Deforestation increased, reaching its peak in the 1980s, as forest lands were opened up for agriculture, cattle pasture, and settlement (Evans, 1999). During this time, approximately two-thirds of the country's extensive tropical forests were cleared (Guindon, 1996; Sánchez-Azofeifa et al., 2001).

There was a dramatic shift in policy in the late 1980s, starting with the removal of subsidies for agricultural products and promotion of eco-tourism (Edelman, 1999). Shortly after, a series of forestry laws were implemented that stopped settlements, prohibited deforestation on private lands, and promoted afforestation and reforestation (Brockett & Gottfried, 2002). Additionally, close to 25% of the country's land area was designated to promote biodiversity conservation (Sánchez-Azofeifa et al., 2003).

In the 1990s, a shift towards stronger environmental values emerged and predominated views of Costa Ricans, which were expressed through their support for new forest conservation laws (Jantzi et al., 1999). In 1994, tourism surpassed the production of bananas and coffee, and became Costa Rica's leading source of foreign exchange (Brockett & Gottfried, 2002). Costa Rica established a program of payment for environmental services in 1997 as a way to combat deforestation and promote reforestation by providing compensation to people who possess forest lands that provide some particular environmental service which include climate-change-mitigation services, hydro services, scenic services and biodiversity services (Robalino & Pfaff, 2013). Three laws form the framework that established the Costa Rican Payment for Ecosystem Services (PES), known in Spanish as "Pago por Servicios Ambientales" (PSA). In 1995, the Environmental Law 7554 mandated a "balanced and ecologically driven environment" for all (Sánchez-Azofeifa, Pfaff, Robalino, & Boomhower, 2007). The Forestry Law 7575 followed in 1996 limiting deforestation even further (Robalino & Pfaff, 2013). In 1998, the Biodiversity Law 7788 focused on rational use of the biodiversity resources along with their conservation (Sánchez-Azofeifa et al., 2007). The PES provides compensation to people who possess forest land that provides some particular environmental service including climate-change-mitigation services, hydro services, scenic services and biodiversity services (Robalino & Pfaff, 2013).

The PES program is managed by FONAFIFO ("Fondo Nacional de Financiamiento Forestal", which roughly translates to "National Fund for Forest Financing"), a semi-autonomous government agency with independent legal status that is in charge of channeling government payments to private forestry owners and protected areas with the goal to protect primary forest, allow secondary forest to recover, and promote reforestation of abandoned pasture and degraded lands (Russo & Candela, 2006). The governing board of FONAFIFO is composed of three representatives of the public sector (one from the Ministry of Environment and Energy, the Ministry of Agriculture, and the National Banking System) and two representatives from the private forest sector who are appointed by the Board of Directors of the National Forest Office (Pagiola, 2008). Since 2001, 3.5% of the fuel tax revenues go directly to fund FONAFIFO (Muller & Patry, 2011; Sánchez-Azofeifa et al., 2007). Additional resources have been secured through agreements with hydroelectric companies including Energía Global, Compañía Nacional de Fuerza y Luz, Hidroeléctrica Platanar and Florida Ice and Farm, in order to protect water resources (Russo & Candela, 2006).

There is currently no standard methodology to properly evaluate the success of the awarded PES contracts or to determine high priority areas that would maximize returns of PES contracts. As a result, reviews for the program have been mixed. Country-wide studies claim that PES was not successful in promoting reforestation or reducing deforestation compared to the national rate (Robalino & Pfaff, 2013; Sánchez-Azofeifa et al., 2007). However, site-specific studies claim that PES was successful in reducing deforestation (Arriagada et al., 2012; Fagan et al., 2013). The discrepancies in the studies may be due, in part, to the lack of proper use or limitations of remote sensing and geographic information system (GIS) data in some studies, along with varying methodologies between the studies**.** At the root of the problem, decision makers and stakeholders do not have appropriate access to GIS and remote sensing data to map/monitor land areas in the program and grant PES contracts efficiently. One common recommendation through different studies is that the PES program would benefit from better targeting of high priority areas to award PES contracts (Arriagada et al., 2012; Daniels et al., 2010; Robalino & Pfaff, 2013; Sánchez-Azofeifa et al., 2007). The ability to identify, monitor, and evaluate PES within Costa Rica is necessary for successful management of the program. The implications of the success of PES are far reaching; since countries in the region also are developing similar programs (Pagiola, 2008).

Remote Sensing for Landscape Assessment

As awareness of the negative effects of forest fragmentation has grown, so has the demand for tools to predict, evaluate, and manage changes in landscape connectivity (Adriaensen et al., 2003). Geographic information systems (GIS) and satellite remote sensing are research techniques that have the capacity to address multiple spatial and temporal scale research questions in a cost-effective manner. The GIS creates a platform that allows for data to be visualized, analyzed, and interpreted in order to understand patterns, trends, and other relationships (Maguire, 1991). Remote sensing is the science of obtaining information through a device that is not in contact with the object under investigation (Lillesand, Kiefer, & Chipman, 2004). In other words, remote sensing provides data, while GIS helps explore the significance of the data.

The first Landsat satellite was launched in 1972 and since then satellite imagery has become readily available and an important source of data to help understand human impacts on the landscape (Baker & Williamson, 2006). The U.S. Landsat Earth observing satellites have been monitoring landscape changes for over forty years and since 2009 the full archive of historical imagery has been released by the U.S. Geological Survey to the public for free online access (Table 1.1) (Colwell, 1983; Wulder et al.2012). General land use classes such as water, agricultural areas, and forests can be easily observed and quantified on Landsat imagery. For the first time in remote sensing history, global access to both historical archives and newly acquired Landsat data provided scientists, policy makers and resource managers the ability to assess changes in land use and land cover and determine trends related to human impacts and how it affects agriculture, forestry, water availability and climate change (Loveland & Dwyer, 2012). Landsat images are regularly used to track forest cover change since forests are a relatively easy cover type to map (Hansen & Loveland, 2012). A time series of satellite imagery can be used to identify and prioritize land areas that should be preserved for conservation and areas that should be restored to connect ecologically important lands (Turner et al., 2003).

Table 1.1 Landsat Mission Summary

Satellite	Time in Service	Spatial Resolution in Meters (Resampled pixel size)	Sensor	Number of Bands
Landsat 1	July 1972 - January 1978	68x83 m (resampled to 60)	MSS	4
Landsat 2	January 1978 - July 1983	80x80 m (resampled to 60)	MSS	4
Landsat 3	March 1978 – September 1983	75x75 m (resampled to 60)	MSS	4
Landsat 4	July 1982 – December 1993	30	MSS	4
Landsat 4	July 1982 – December 1993	30	TM	7
Landsat 5	March 1984 – January 2013	30	TM	7
Landsat 6	Failed to Reach Orbit			
Landsat 7	April 1999 to Present	30	ETM+	8
Landsat 8	February 2013 to Present	30	OLI and TIRS	11

Remotely sensed satellite imagery, especially in the form of Landsat imagery, has been used to study the Costa Rican landscape since the 1970’s (Joyce, 2006). Early Multispectral Sensor (MSS) Landsat imagery has a spatial resolution (pixel size) of 68 x 83, 80 x 80 and 75 x 75 m and starting in 1984 with the launch of the Thematic Mapper sensor on Landsat 5, the imagery resolution was improved to 30 x 30 m. Higher resolution imagery such as RapidEye (5-m spatial resolution) has been used recently by GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit, which is the German counterpart to the USAID), to help measure the amount of forest cover in Costa Rica (SINAC & REDD-CCAD-GIZ, 2015).

Unfortunately, RapidEye imagery is cost-prohibitive to local conservation groups and the CBPC Council.

The purpose of the CBPC and one of the goals of the CBPC Initiative is to turn the CBPC from a designated conservation area into a functional wildlife corridor. Effective management and monitoring of land use changes requires spatial-temporal data in order to incorporate land use patterns, geomorphology, and hydrologic and vegetation parameters (Huete & Ustin, 2004). Successful corridor design involves considering a corridors functional connectivity (which is connectivity that is based on species behavior) and its structural connectivity (which is connectivity based on the landscape structures) (Kindlmann & Burel, 2008). The extensive data set provided by the Landsat missions can help track forest cover change within the corridor and provide valuable information in order to assess the structural and functional connectivity of the corridor as will be shown in this dissertation.

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CHAPTER 2

FOREST COVER CHANGE IN THE BELLBIRD BIOLOGICAL CORRIDOR BETWEEN 1974 AND 2014

Introduction

Costa Rica has undergone dramatic economic and environmental policy shifts since the 1950s, the results of which can be seen by observing how forest cover has fluctuated over the past 60 years. Before the 1980s, for example, the Costa Rican economy relied mostly on large agricultural exports (Booth et al., 2014) and the policies of the time were reflected by forested lands being cleared and opened for agriculture, cattle pasture, and settlement (Evans, 1999). This frontier expansion exacerbated deforestation and it is estimated that during this time two-thirds of the country's extensive tropical forests were cleared (Guindon, 1996; Sánchez-Azofeifa et al., 2001). There was a dramatic shift in policy in the late 1980s, starting with the removal of subsidies for agricultural products and promotion of eco-tourism (Edelman, 1999), along with the collapse of the beef industry (Calvo-Alvarado et al., 2009). Shortly after, a series of forestry laws were implemented that stopped settlements, prohibited deforestation on private lands, and promoted afforestation and reforestation (Brockett & Gottfried, 2002). Current forest cover is estimated at 53% based on 2012 satellite imagery (SINAC & REDD-CCAD-GIZ, 2015).

In order to prioritize management in any designated area, we must understand current land use/land cover and how it contributes to conservation goals. Understanding the structural connectivity is important for successful wildlife corridor management (Adriaensen et al., 2003). The CBPC Council understands the need to address this information gap. In March of 2011, the

CBPC Initiative published a 5-year strategic plan (Welch et al., 2011). Within the strategic plan, the need to generate a baseline of forest connectivity and current land use within the CBPC was identified. There have been nation-wide (SINAC & REDD-CCAD-GIZ, 2015) and local (Chinchilla Ramos, 2015) studies looking at forest cover by using RapidEye satellite imagery from 2012. However, replicating and updating these studies by local stakeholders are cost prohibited since RapidEye imagery is not freely available. These studies are also limited in scope and are already a bit dated since they only analyze imagery from 2012. There have also been nation-wide studies tracking forest cover change in Costa Rica (Joyce, 2006; Sánchez-Azofeifa et al., 2001) using freely available NASA satellite imagery, but none specifically tracking forest cover in the CBPC or providing the results and data to local policy makers.

Research Goal

The overall goal of this research is to monitor forest cover changes within the CPBC by analyzing NASA satellite imagery between 1974 and 2014. Additionally, this study identified and quantified land cover types transitioning to forest and land covers to which forested areas are converted. By determining these land cover changes and creating a current baseline of forest cover within the CBPC, local stakeholders and policy makers will be one step closer to turning the CBPC into a functional wildlife corridor.

Data and Methods

Satellite Imagery

Landsat imagery was obtained at no charge from the U.S. Geological Survey (USGS) Earth Explorer (available at http://earthexplorer.usgs.gov). Cloud free images were used when available. In cases where there was cloud cover, images acquired close in time were mosaicked from different Landsat Paths since the CBPC can be found on the western segment of Landsat tiles corresponding to Path 16 Row 53 and the Eastern section of Path 15 row 53 on Landsat images dating from 1984 until the present (Figure 2.1). Being near the equator, Costa Rica only has two seasons. The sunny, dry season runs from December to April and the cloudy, wet season runs from May to November (Haber et al., 2000). The majority of images were acquired between January and March in order to minimize cloud cover (Table 2.1). The study area boundary was adjusted slightly to exclude a small area in the northeastern section of the CBPC for which cloud free imagery was not available for the entire time series (Figure 2.2).

Table 2.1 Landsat Imagery used to Derive Land Cover within the CBPC (*Image resolution resampled by USGS)

Date Acquired	Image ID	Path	Row	Resolution (m)
3/17/1974	LM10160531974076AAA05	16	53	60*
2/26/1976	LM20160531976057GMD03	16	53	60*
1/23/1979	LM20160531979023AAA04	16	53	60*
1/15/1984	LM40160531984015AAA03	16	53	60*
1/24/1984	LM40150531984024AAA03	15	53	60*
1/12/1986	LT50160531986012AAA03	16	53	30
1/21/1986	LT50150531986021XXX03	15	53	30
1/16/1990	LT50150531990016CPE03	15	53	30
2/14/1998	LT50160531998045AAA01	16	53	30
1/3/2003	LE70160532003003EDC00	16	53	30
1/12/2003	LE70150532003012EDC00	15	53	30
3/6/2011	LT50160532011065CHM00	16	53	30
2/19/2014	LC80150532014050LGN00	15	53	30
2/26/2014	LC80160532014057LGN00	16	53	30

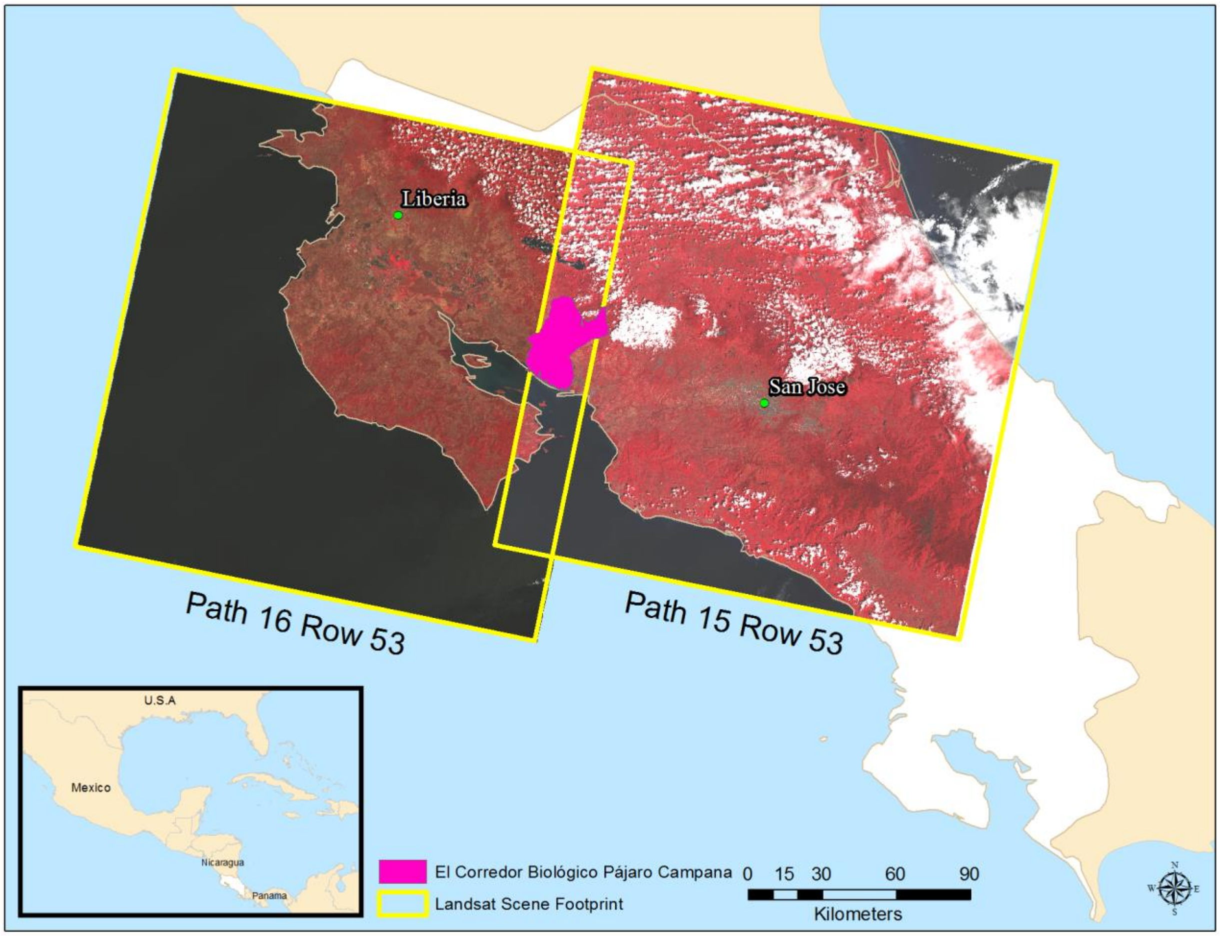

Figure 2.1 Landsat Scene Footprint: the CBPC, shown in magenta, can be found on the western segment of Landsat tiles corresponding to Path 16 Row 53 and the Eastern section of Path 15 row 53 on Landsat images dating from 1984 until the present. Imagery before 1984 encapsulate the entire study area in a single tile.

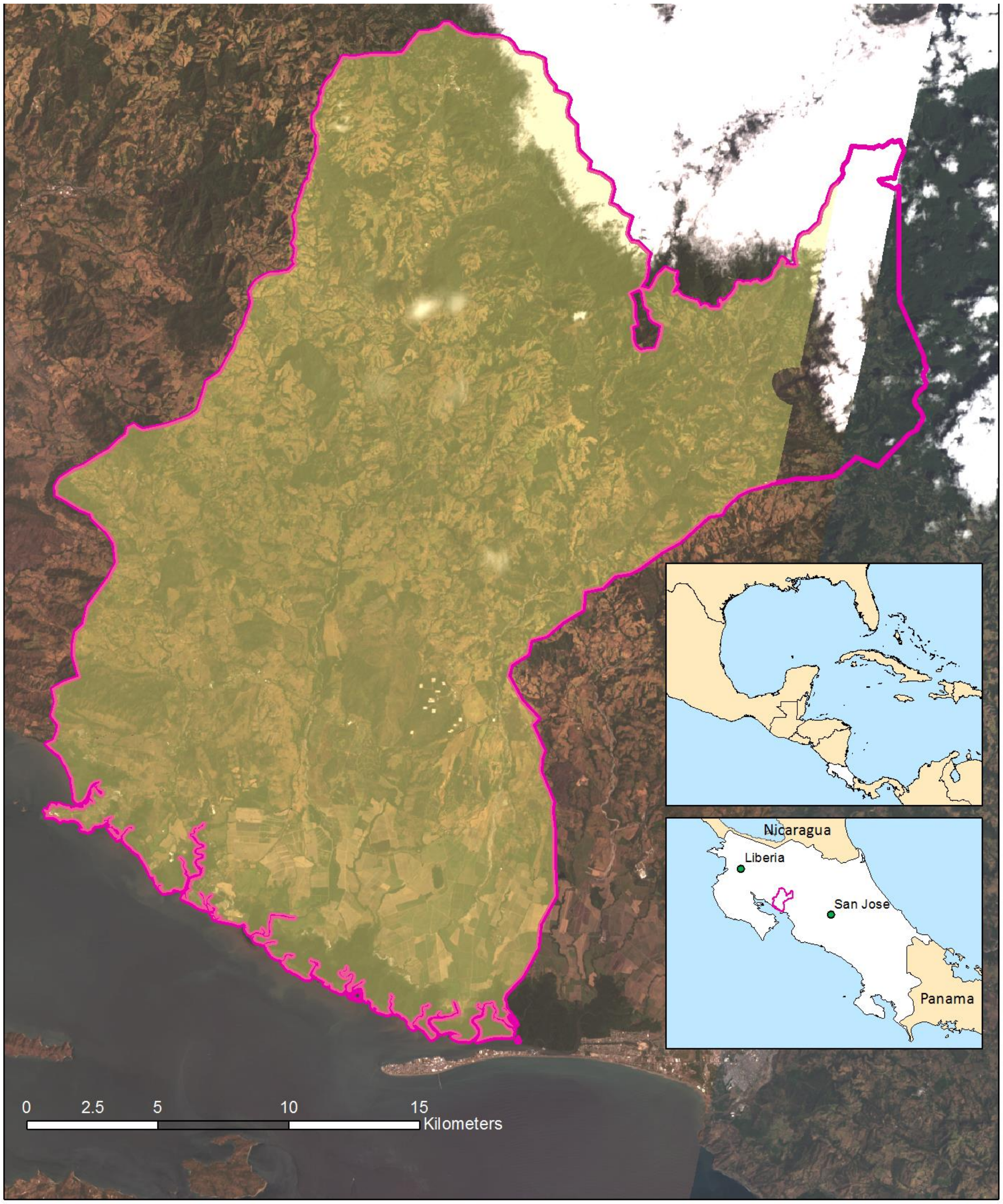

Figure 2.2 The Adjusted Study Area: the magenta line outlines the boundary of the CBPC. The area highlighted in yellow is the study area that was used for temporal comparison from 1974 to 2014 due to cloud cover in some of the imagery.

Image Processing - Atmospheric Correction

After collecting the images, atmospheric correction was performed by using the Quick Atmospheric Correction (QUAC, (Bernstein et al., 2012)) tool in ENVI 5.1 (Exelis, Tysons Corner, Virginia, USA; http://www.exelisvis.com/) as a precaution since our study site includes cloud forests and cloud were present in all Landsat scenes. The QUAC process uses an in-scene approach, which only requires approximate specifications of the sensor band locations and their radiometric calibration as long as there are 10 diverse materials in a scene and that there are sufficiently dark pixels in a scene to help determine baseline spectrum (Bernstein et al., 2012). Since no metadata is required, this process could be applied to all Landsat images, unlike other common atmospheric correction algorithms.

Image Processing - Wide Dynamic Range Vegetation Index

A Wide Dynamic Range Vegetation Index (WDRVI, Gitelson, 2004) was used to measure the amount of forest cover within the CBPC. The WDRVI is a modification of the Normalized Difference Vegetation Index (NDVI) that has been used to track temporal changes in biomass (Sader & Winne, 1992). The WDRVI overcomes the saturation seen in NDVI in areas of high biomass by enhancing the dynamic range while using the same bands as the NDVI, facilitating vegetation classification (Gitelson, 2004). Through trial and error, we decided to use a 0.2 coefficient since it provided us with the largest range for WDRVI values.

$$WDRVI = \frac{0.2 * \rho NIR - \rho RED}{0.2 * \rho NIR + \rho RED}$$

Image Processing - Image Classification

Pixels were classified based on their WDRVI values, elevation, and shape into one of the following categories: Forested, Non-Forested, Mangrove, Aquaculture, and Industrial Agriculture (Table 2.2 and Figure 2.3). First, WDRVI values were used to separate pixels into three main categories: Forested, Non-Forested and Aquaculture. Non-Forested areas included pastures, riverbanks, towns, and small-scale agricultural farms. Mangrove areas were derived from forested pixels by using the method developed by Long and Skewes (1996) where class values were re-assigned from Forest to Mangroves based on nearness to the Gulf of Nicoya, elevation, and visual comparison using current Google Earth Imagery (Google Inc.; https://www.google.com/earth/).

Since WDRVI was not effective in classifying industrial agricultural areas due to varying levels of WDRVI values resulting from the type and growth stage of the crops, whether or not the land was tilled, and the use of fertilizers (Figure 2.7). When pixel-based classification is not effective, like in the case of industrial agricultural areas, using shape, pattern, and texture can be used to differentiate different land cover types with similar spectral signatures (Haralick & Shanmugam, 1973; Van der Werff & Van Der Meer, 2008). Industrial agricultural areas included broad-scale farming and look different than any other land cover based on sharp, straight lines across the landscape (Figure 2.5 and Figure 2.7), that are not present in any other land cover types. Industrial agricultural areas were digitized based on texture, shape, and pattern. Table 2.2 summarizes the WDRVI values and additional factors used to classify the pixels.

Table 2.2 Image Classification Variable Summary: List of WDRVI range and variables used to classify each of the five classes.

Class	WDRVI Range		Additional Variables Used
	from	to	
Aquaculture	-1.0	-0.5	Elevation and proximity to the ocean
Non-Forested	-0.5	0.12	None
Forested	0.12	0.62	Elevation
Mangrove	0.12	0.62	Elevation and proximity to the ocean
Industrial Ag	-0.6	0.3	Texture, shape, and pattern

Figure 2.3 Land Cover Classes Images. Clockwise from the top: A) Forest, B) Non-Forested (e.g. Pasture), C) Industrial Agriculture, D) Aquaculture, and E) Mangrove

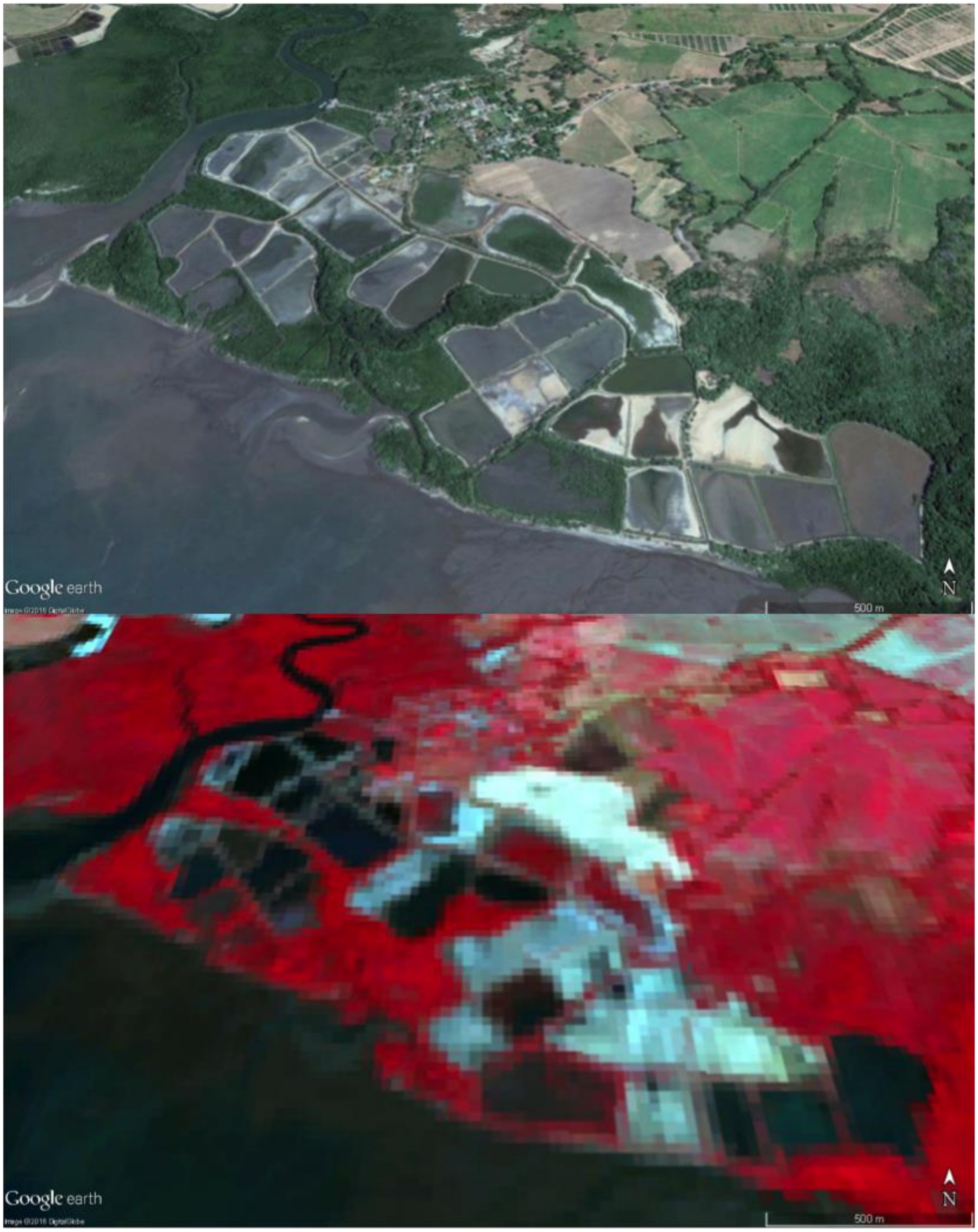

Figure 2.4 Satellite View of the Aquaculture Class: The image on the top is a 2016 Google Earth image of aquaculture ponds in the CBPC. The image on the bottom is the 2014 Landsat image showing the near infrared band of the same area.

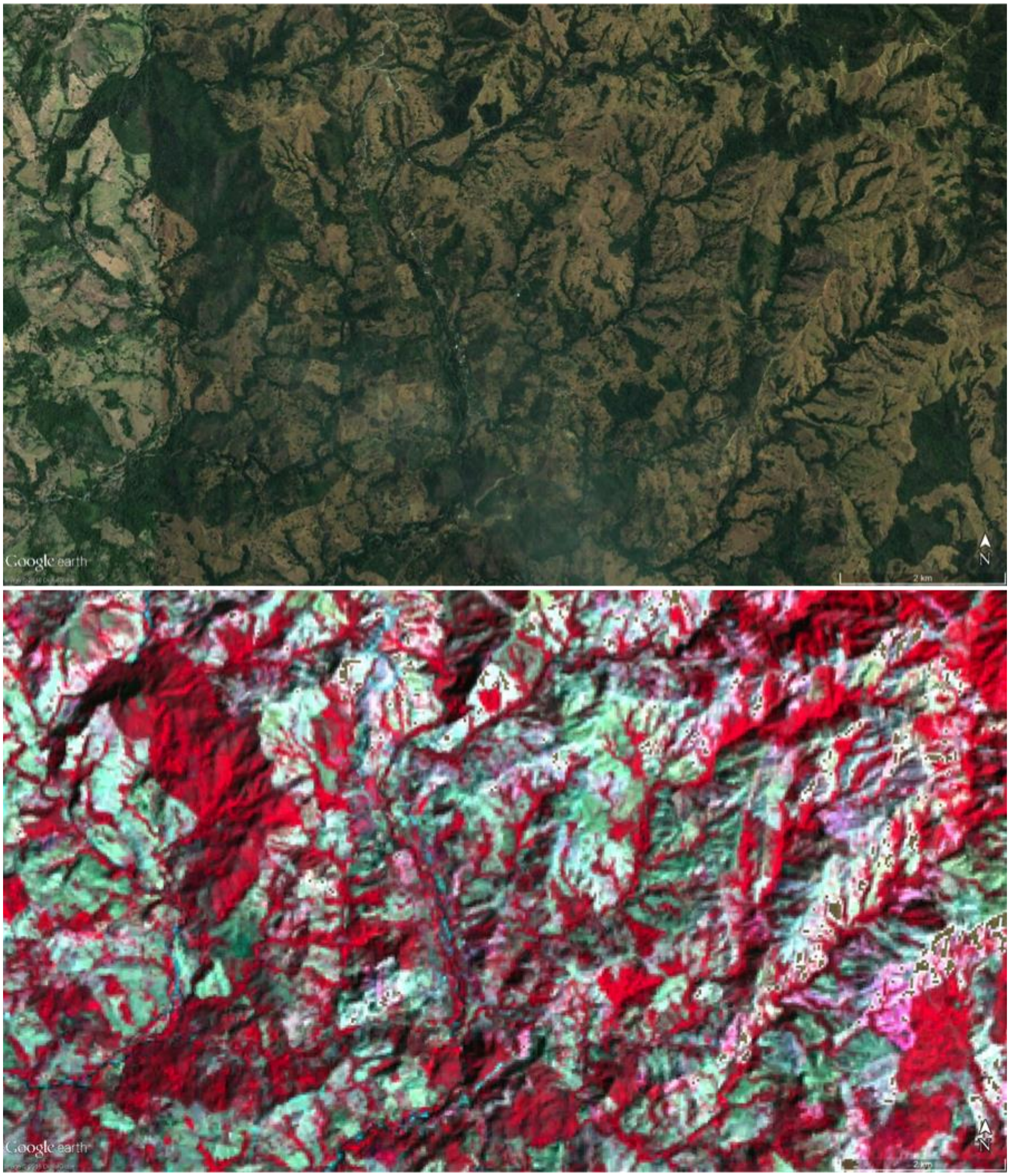

Figure 2.5 Satellite View of the Forest and Non-Forest Classes: The image on the top is a 2016 Google Earth image of a section of the CBPC where the green areas are forests and beige areas are non-forested areas, mostly pastures. The image on the bottom is the 2014 Landsat image showing the near infrared band of the same area, where the bright red areas are forested areas and the rest are non-forested areas.

Figure 2.6 Satellite View of the Mangrove Class: The image on the top is a 2016 Google Earth image of mangroves in the CBPC. The image on the bottom is the 2014 Landsat image showing the near infrared band of the same area.

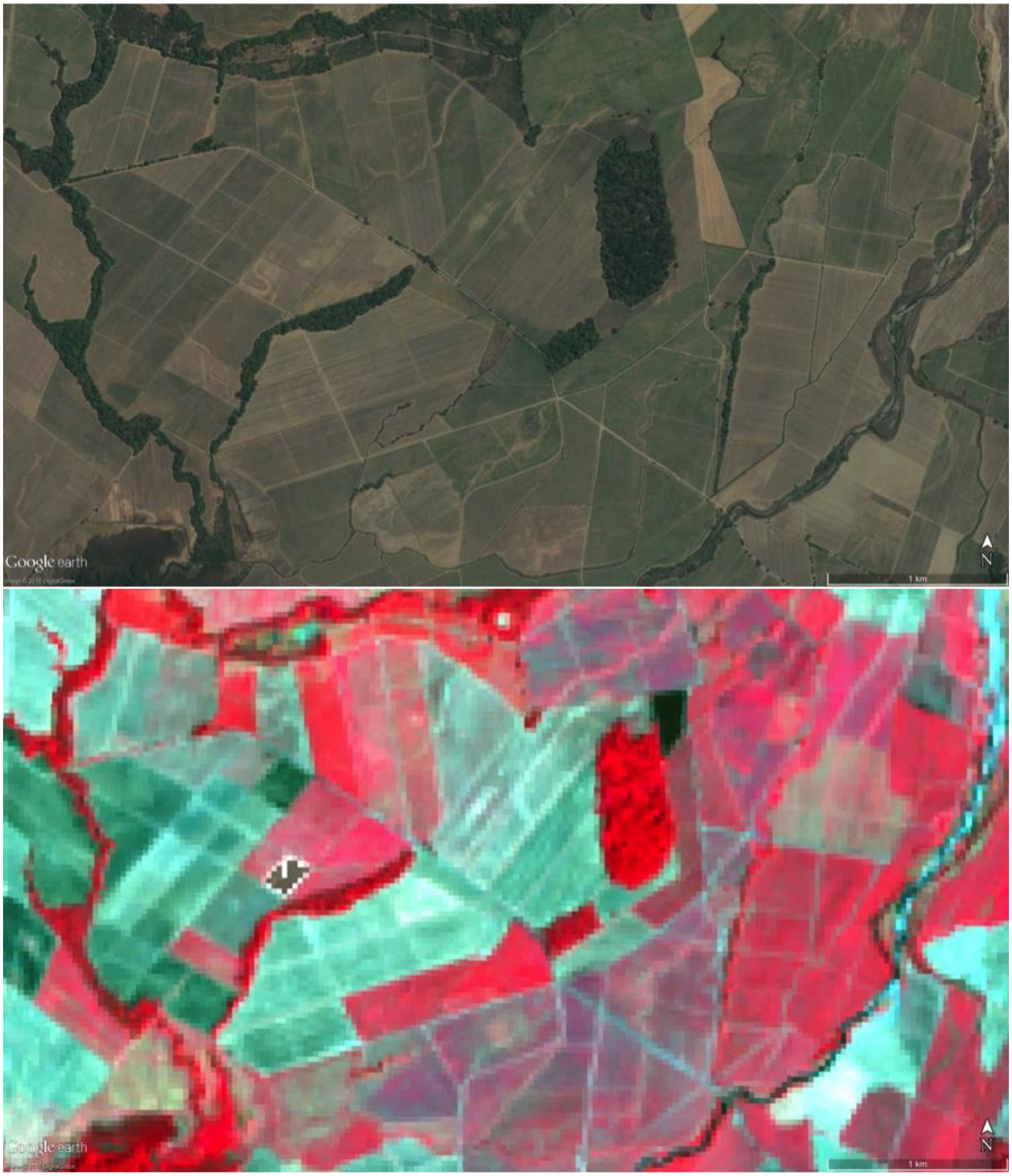

Figure 2.7 Satellite View of the Industrial Agriculture Class: The image on the top is a 2016 Google Earth image of areas of large industrial agriculture in the CBPC. The image on the bottom is the 2014 Landsat image showing the near infrared band of the same area. Please note the distinctive pattern of this class and the varying degree of red in the bottom image, which is why there was a large range of WDRVI values.

Image Processing - Post Classification Change Detection

Once classified, the data were imported into ArcMAP 10.3 (ESRI, Redlands, California, USA; http://www. esri.com/) in order to generate summary statistics for each land use class and to generate maps for comparison for each year of study (Figures 2.8 through 2.17). A post classification change detection was used in ArcMAP to map changes over the landscape. This method has the advantage of indicating the nature of the change (e.g. forest converted to pasture) while minimizing the effects of using multi sensor images (Mas, 1999). It is important to note that in this technique, the final thematic accuracy is dependent on the classification accuracy of the individual image (Hussain et al., 2013) stressing the importance of an accuracy assessment.

Results

Land Cover Classification Maps

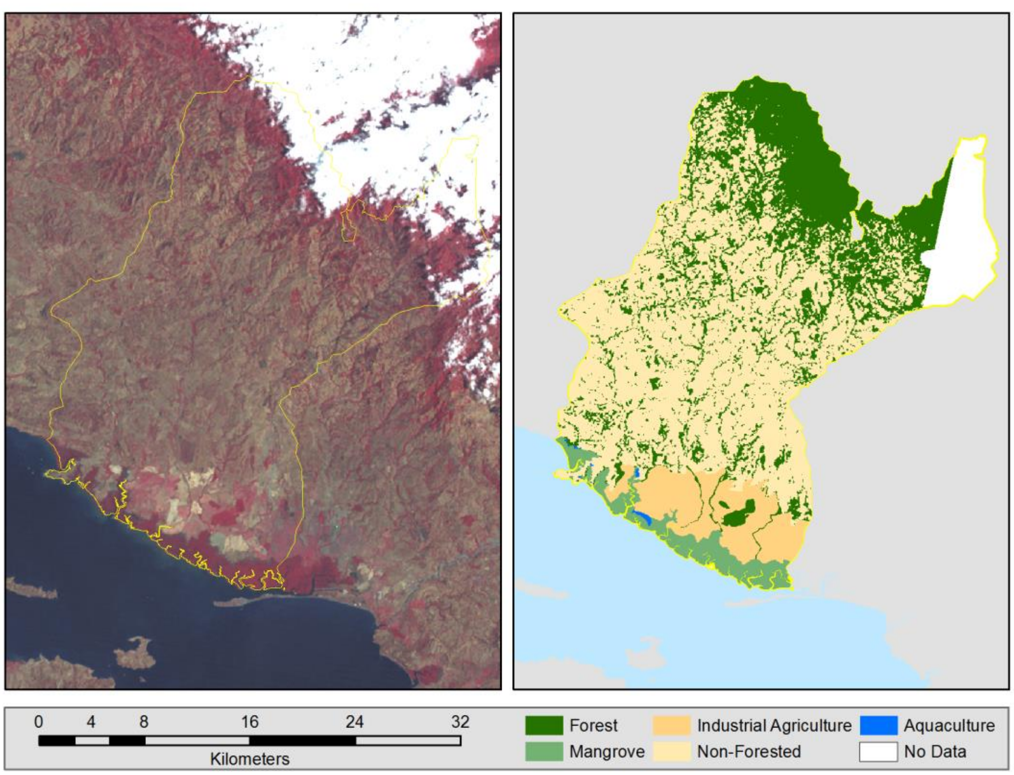

Figure 2.8 1974 Land Cover Map of El Corredor Biológico Pájaro Campana

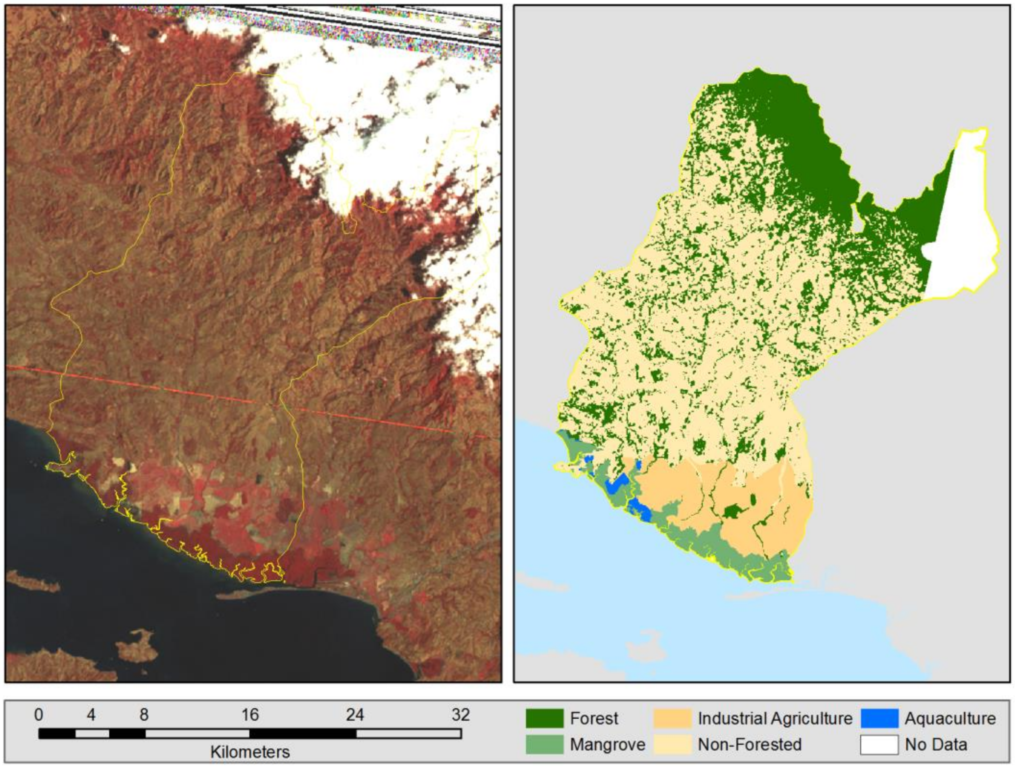

Figure 2.9 1976 Land Cover Map of El Corredor Biológico Pájaro Campana

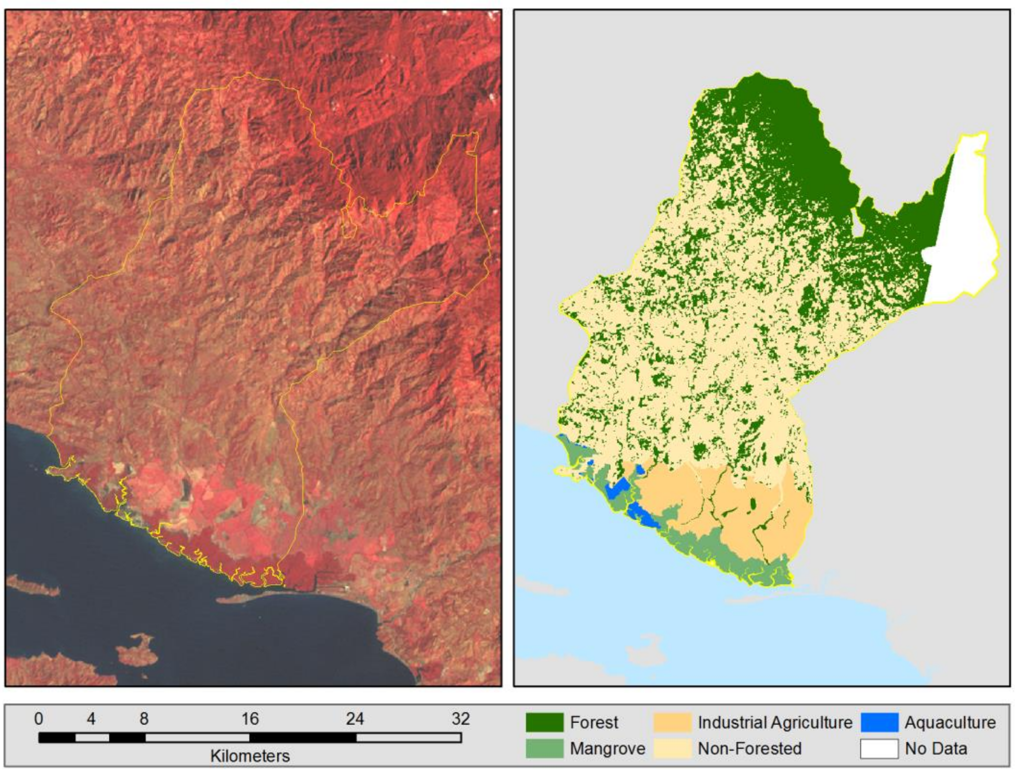

Figure 2.10 1979 Land Cover Map of El Corredor Biológico Pájaro Campana

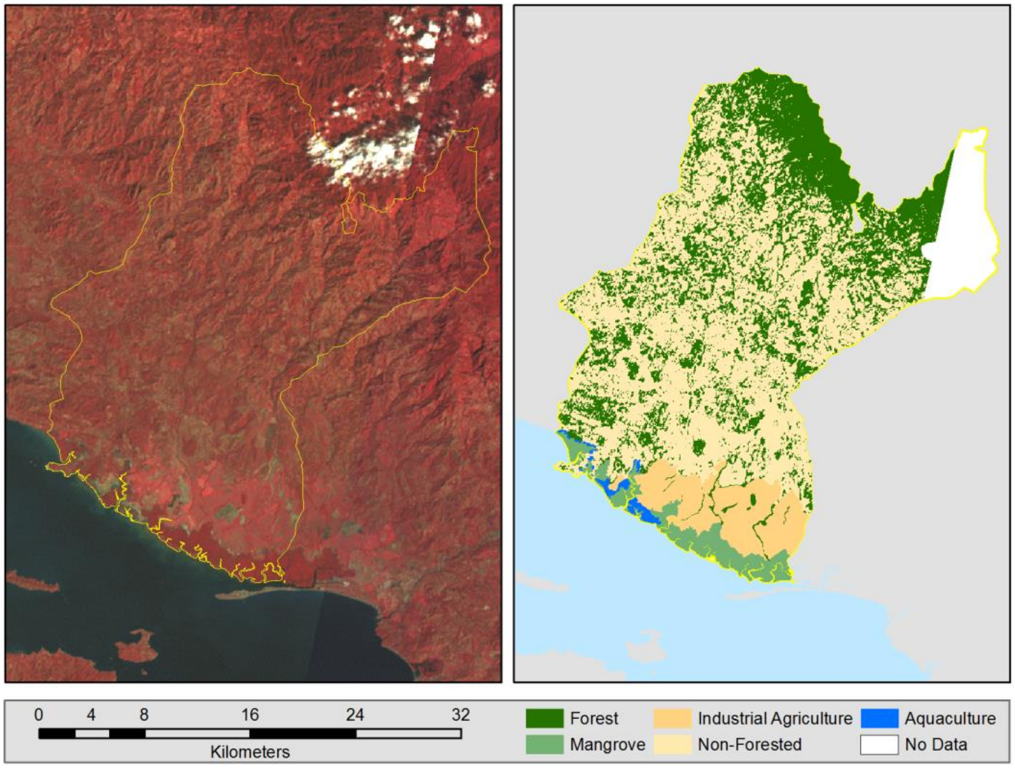

Figure 2.11 1984 Land Cover Map of El Corredor Biológico Pájaro Campana

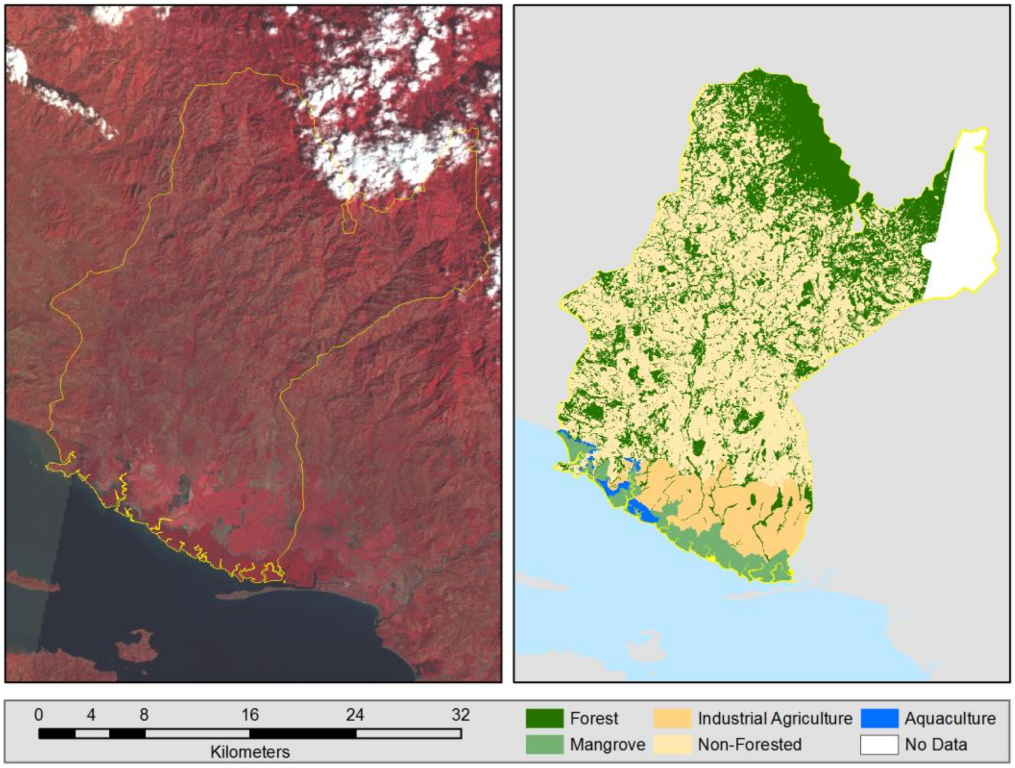

Figure 2.12 1986 Land Cover Map of El Corredor Biológico Pájaro Campana

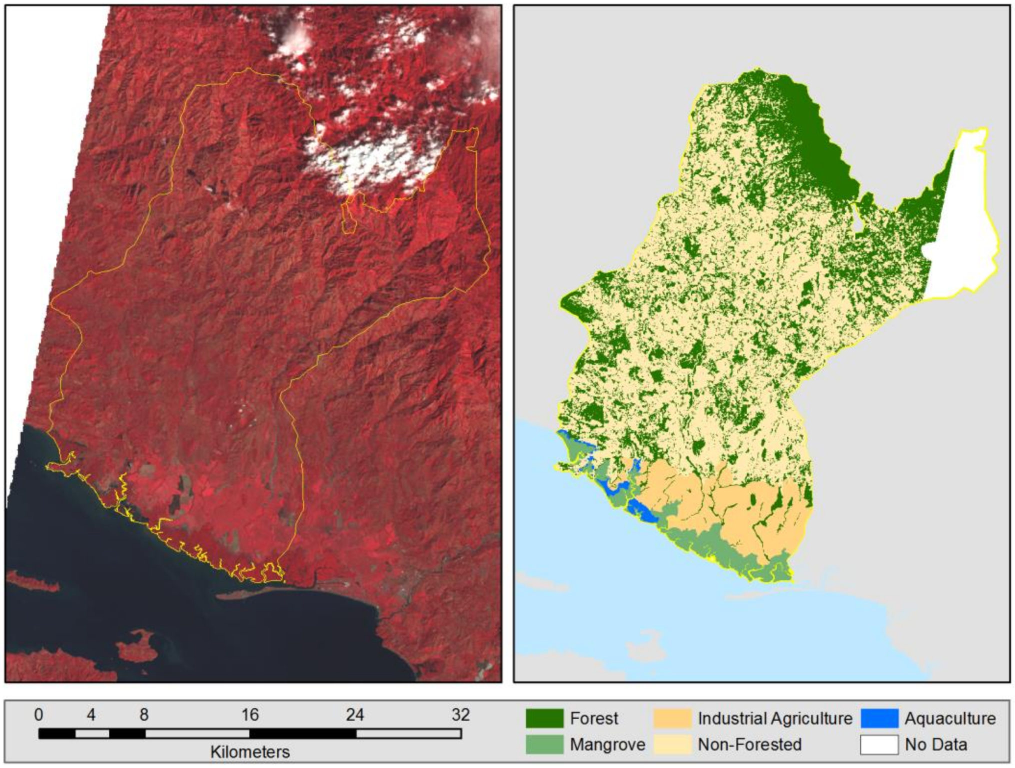

Figure 2.13 1990 Land Cover Map of El Corredor Biológico Pájaro Campana

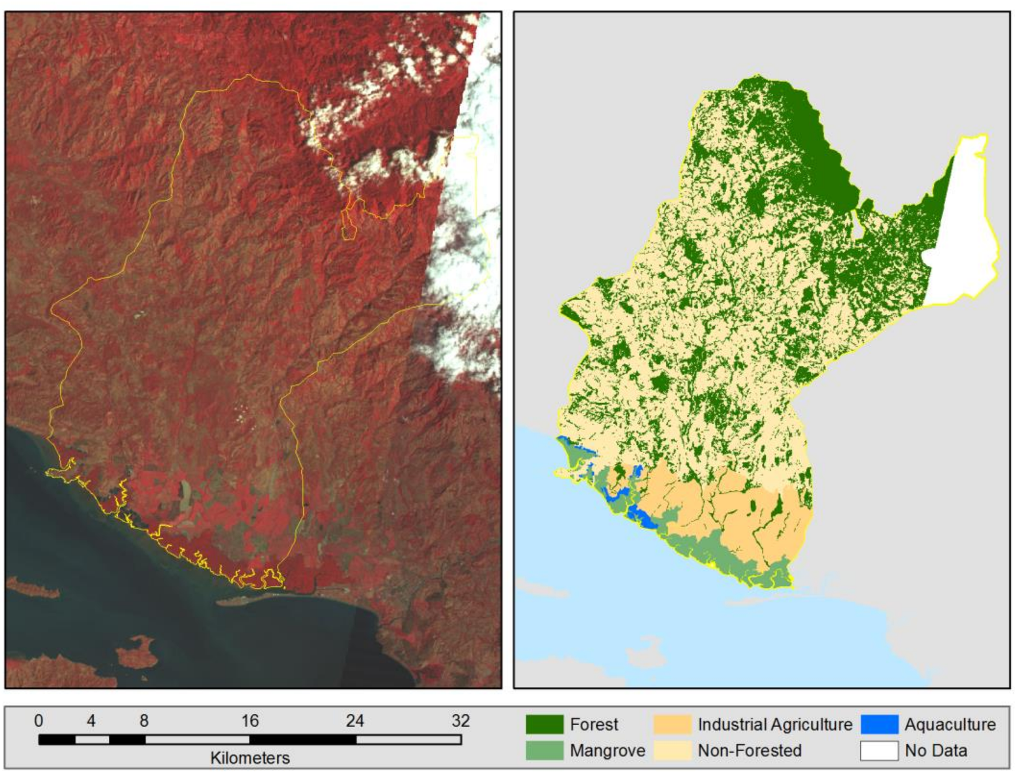

Figure 2.14 1998 Land Cover Map of El Corredor Biológico Pájaro Campana

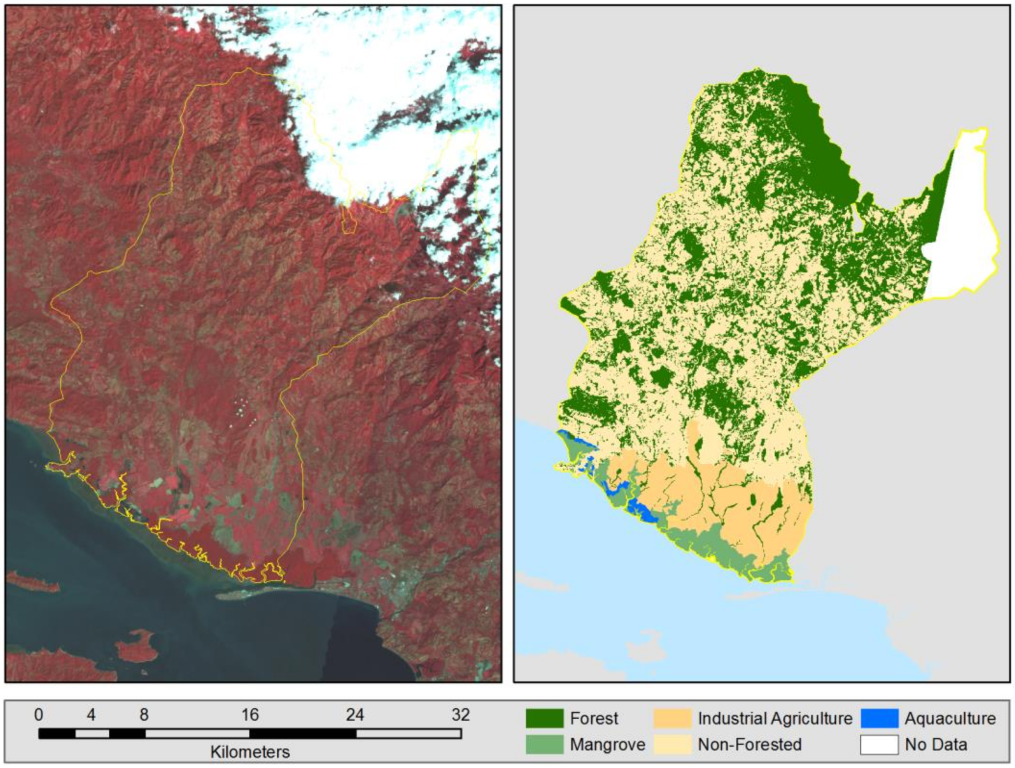

Figure 2.15 2003 Land Cover Map of El Corredor Biológico Pájaro Campana

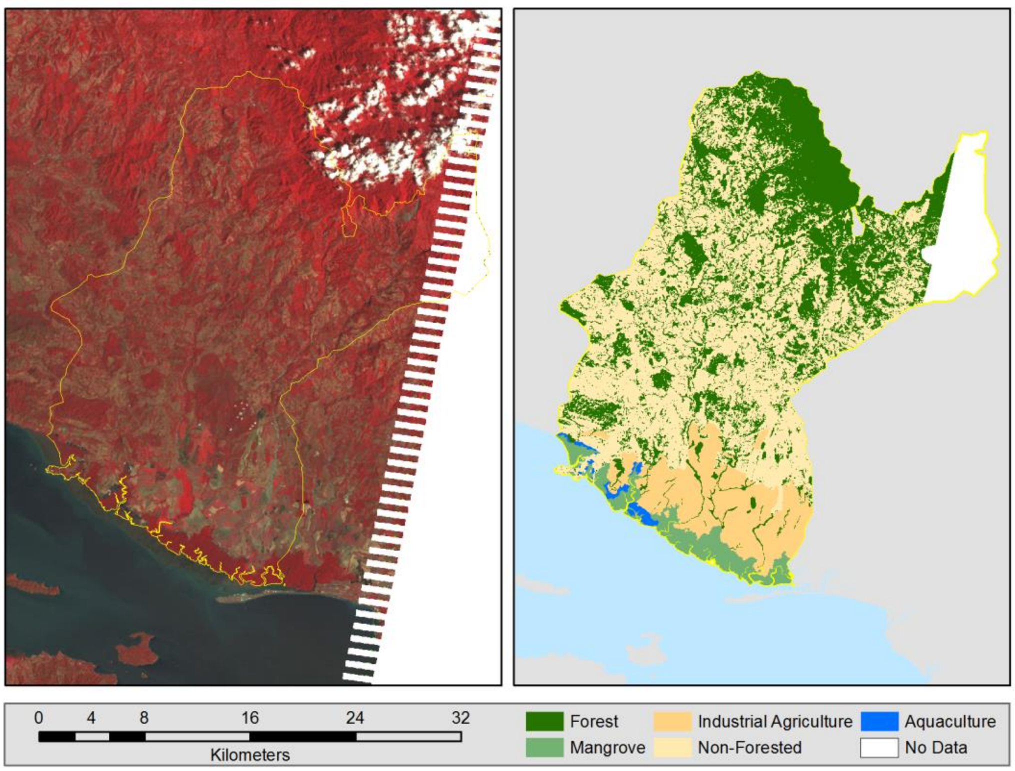

Figure 2.16 2011 Land Cover Map of El Corredor Biológico Pájaro Campana

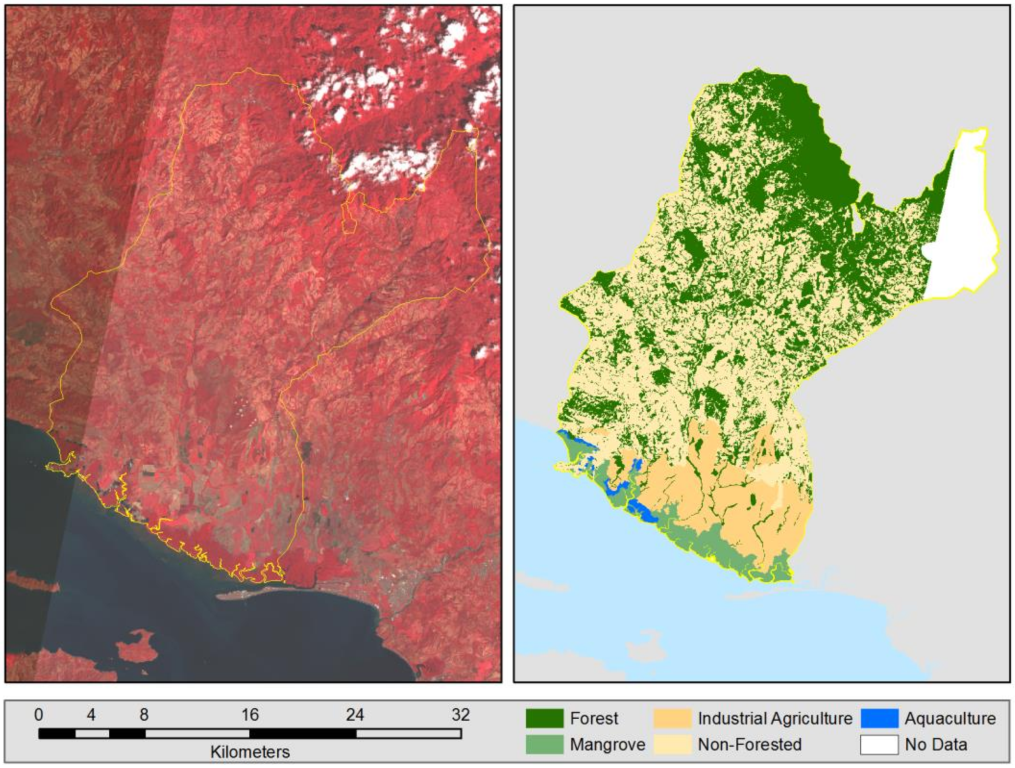

Figure 2.17 2014 Land Cover Map of El Corredor Biológico Pájaro Campana

Land Cover Change

Between 1974 and 2014, non-forested areas covered most of the CBPC, ranging from 57% to 46%. The second most abundant class was forested areas which had a coverage of about 30% and increased to 37% of the total area. Industrial agricultural was the third most abundant class covering about 10% of the total area. Mangroves covered about 5% of the total area, while aquaculture covered about 1%. The total area for each class is summarized in Table 2.3 and the percentage for each class is summarized in Table 2.4. Figure 2.14 shows the data as a line graph to help visualize the change of coverage between each year.

Table 2.3 Land Cover Change Area in Hectares Separated by Year

Class/Year	1974	1976	1979	1984	1986	1990	1998	2003	2011	2014
Aquaculture	92	382	457	458	449	435	393	384	414	414
Forest	18574	18394	20555	20266	19576	19839	21916	22690	21567	23112
Industrial Agriculture	5497	6383	6267	5239	5507	5616	5999	6776	7193	7544
Mangrove	2872	2823	2715	2614	2634	2561	2578	2503	2578	2584
Non-Forested	35120	34269	32224	33577	33997	33705	31268	29805	30409	28507

Table 2.4 Land Cover Change Area as a Percentage Separated by Year

Class/Year	1974	1976	1979	1984	1986	1990	1998	2003	2011	2014
Aquaculture	0	1	1	1	1	1	1	1	1	1
Forest	30	30	33	33	31	32	35	37	35	37
Industrial Agriculture	9	10	10	8	9	9	10	11	12	12
Mangrove	5	5	4	4	4	4	4	4	4	4
Non-Forested	57	55	52	54	55	54	50	48	49	46

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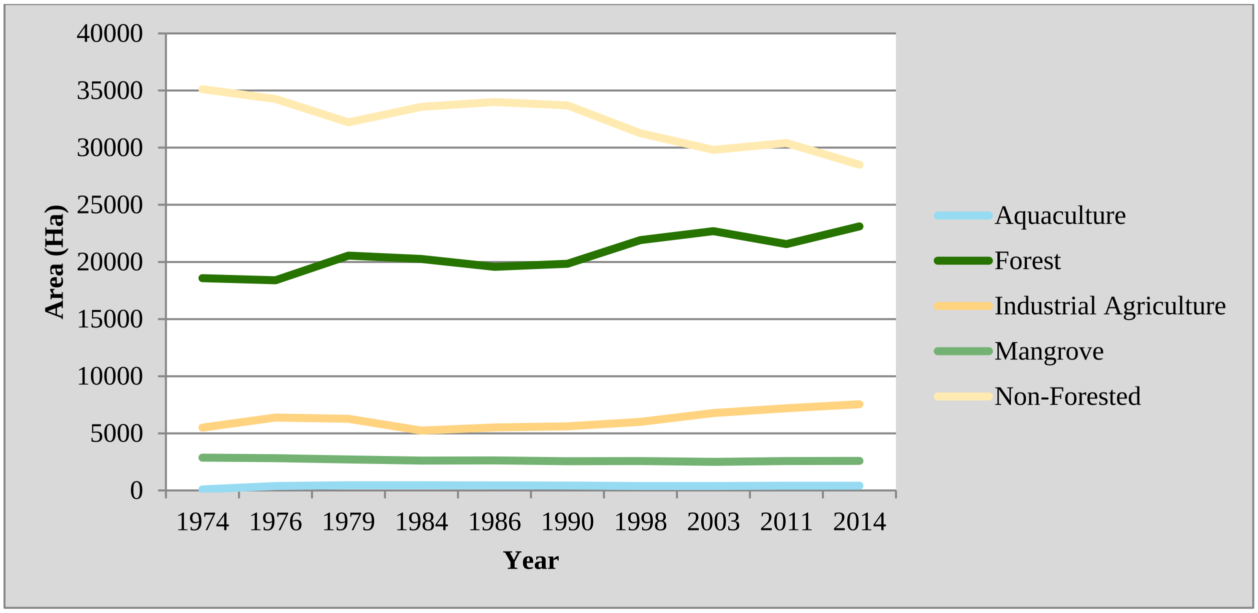

Figure 2.18 Land Cover Change in El Corredor Biológico Pájaro Campana between 1974 and 2014

Accuracy Assessment

We performed a thematic accuracy assessment of the 2014 image classification using ground truth points collected in the field with a hand-held GPS and we assigned them into one of the five classes. We visited the CBPC twice in the in the Fall 2014, once in September and at the end of November. Additional points were collected during the Spring of 2015. A total of 259 points were collected across the elevation of range from zero meters to 1623 meters above sea level (Table 2.5). Based on our collected points, our 2014 classified map has 93% accuracy (Table 2.6) with a kappa value of 0.924 (Table 2.7). The Mangrove and Aquaculture classes were predicted well, with 100% accuracy between the predicted and observed sampling points. The Forested, Non-Forested, and Industrial Agriculture classes had predicted points that were wrongly classified as one of the other two classes. In all of these three cases, the accuracy was higher than 89.5%.

Table 2.5 Sampling Points Summary and Estimated Coverage Area per Class.

Class	Estimated Area (%)	Sampling Points
Aquaculture	1	7
Forest	37	98
Industrial Agriculture	12	33
Mangrove	4	7
Non Forested	46	114

Table 2.6 Accuracy Assessment Results: Confusion matrix showing results of an accuracy assessment for the classification of land cover from the 2014 Landsat imagery. Overall 93.4% accuracy between the predicted and observed classes.

		Observed						
		Forest	Mangrove	Aquaculture	Non-Forest	Industrial Ag	Total	User's Accuracy
Predicted	Forest	94	0	0	12	0	106	88.68
	Mangrove	0	7	0	0	0	7	100.00
	Aquaculture	0	0	7	0	0	7	100.00
	Non-Forest	4	0	0	102	1	107	95.33
	Industrial Ag	0	0	0	0	32	32	100.00
	Total	98	7	7	114	33	259	
	Producer's Accuracy	95.92	100.00	100.00	89.47	96.97		Overall: 93.44

Table 2.7 Kappa Statistics Results Summary: With a Kappa value of 0.924, there is a low probability of predicted and observed points agreeing by chance.

	Forest	Mangrove	Aquaculture	Non-Forest	Industrial Ag	Total
Agreement	94	7	7	102	32	242
By Chance (%)	15.49	0.07	0.07	18.18	1.57	35.39

Kappa	0.9240

Post Classification Change Detection Results

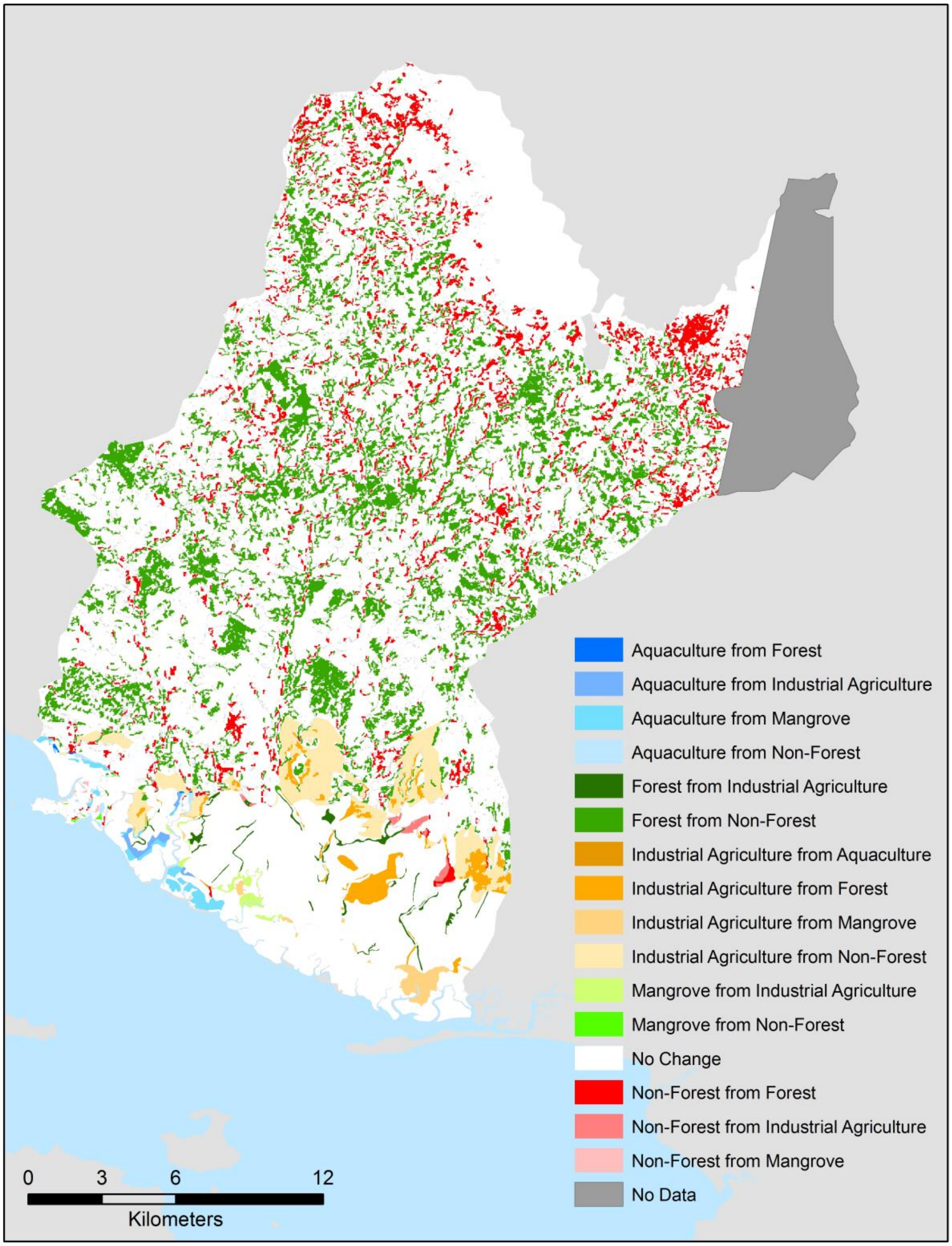

Figure 2.19 Land Cover Change Detection in El Corredor Biológico Pájaro Campana between 1974 and 2014

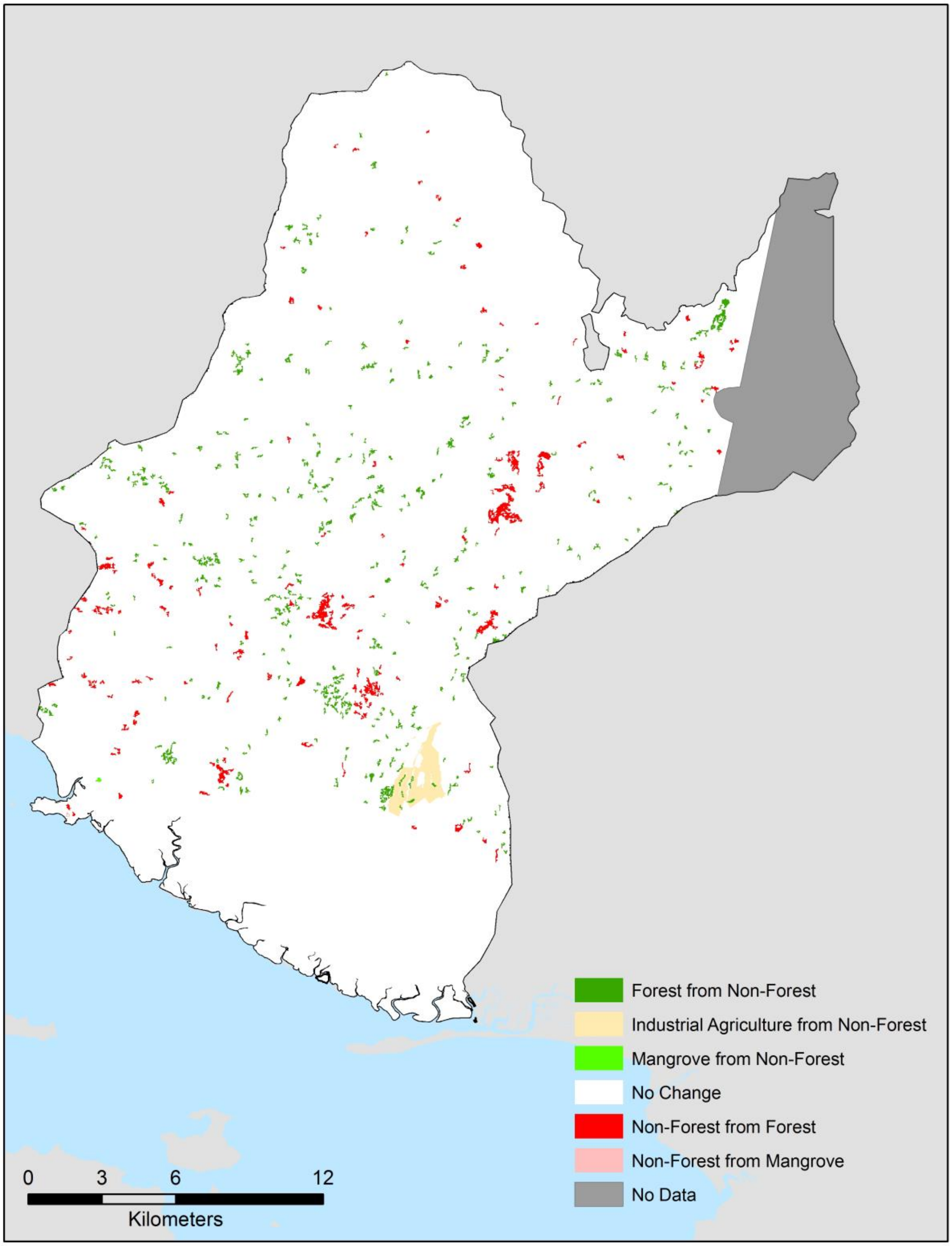

Figure 2.20 Land Cover Change Detection in El Corredor Biológico Pájaro Campana between 2011 and 2014

Discussion

Overall there was a net gain for forest cover within the CBPC over the 40-year time period between 1974 and 2014, which is also a trend seen across the country (Sills et al., 2008). Nationwide in Costa Rica, forests have increased where pastures and traditional crops were abandoned (Jadin, Meyfroidt, & Lambin, 2016). According to our results, forest cover accounted for about 30% (18,574 ha) of our study area in 1974 (Figure 2.8) and steadily increased to about 37% (23,112 ha) in 2014 (Figure 2.17). There was a dip in forest cover in the 2011 image that was due to a forest fire that spread to surrounding areas determined by our accuracy assessment (Figure 2.20). There has also been an increase in the amount of industrial agriculture across the CBPC that covered about 12% (7,544 ha) of the total area in 2014, up from 9% (5,497 ha) in 1974.

Our change detection analysis also shows the increase in Forested and Industrial Agricultural areas are coming from Non-Forested areas (Figure 2.18). However, despite the net gain of forest cover, there have been areas that have been deforested. A similar trend has been observed in the Northeastern region of Costa Rica, where there was a 50% reduction in deforestation rates after 1996, even though pastures and native and exotic tree plantations were being converted into pineapple cultivation (industrial agriculture) (Fagan et al., 2013). In both cases, the amount of non-forested area has decreased, which has been due in part to stricter environmental laws and the promotion of ecotourism (Edelman, 1999). The middle elevation portion of the CBPC has increased in forest cover, which is helping link the cloud forest to the mangrove which is crucial in turning the CBPC from a designated conservation area into a functional wildlife corridor.

Despite an increase in forested areas and a decrease in pastures, there has also been an increase in industrialized agricultural. In Costa Rica, pineapple production has been shown to simplify and homogenize the landscape while decreasing connectivity, decreasing total tree cover and further isolating forest patches (Shaver et al., 2015). Areas with grasslands and agriculture in Costa Rica have lower species richness than forests (Daily et al., 2003) and studies have shown pasture and agriculture avoidance by frogs (Nowakowski et al., 2013) and birds (Hadley & Betts, 2009; Lindell et al., 2004). Even though some animals can move across a non-forested landscape, pastures and agricultural areas can have negative effects at different stages of an animal's lifecycle. For example, white-throated robin (*Turdus assimis*) fledglings have an increased likelihood of dying in non-forested areas in Costa Rica (Cohen et al., 2004). Identifying the current tree coverage of the corridor was important since single trees and windbreaks can facilitate animal movement and reforestation within the Monteverde region (Harvey, 2000).

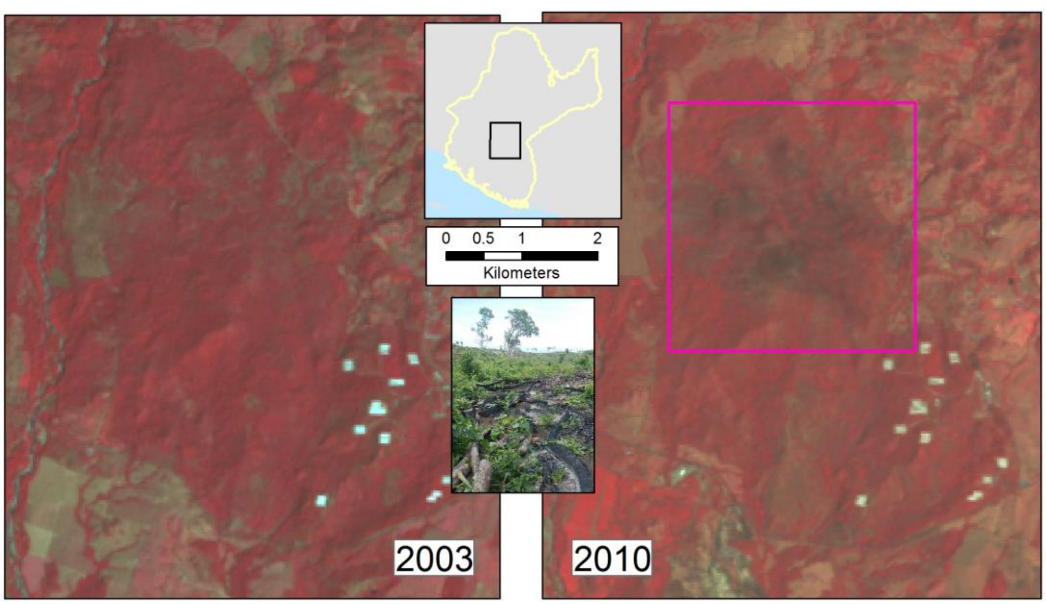

Figure 2.21 Burn Scar From a Wildfire in El Corredor Biológico Pájaro Campana Visible in the 2010 Image.

There was an increase in area used for aquaculture from 92 ha in 1974 to 382 ha 1979 at which point the amount of aquaculture leveled off and remained constant at around 430 ha. The amount of mangrove area has also been constant at about 4% since 1979. Effective legislation and a growing eco-tourism have allowed Costa Rica show the highest proportion of intact mangrove forest compared to Panama, Colombia, and Ecuador (Jiménez, 2004; López-Angarita et al., 2016). This is great news since the Pacific Coast of Costa Rica, in particular the Gulf of Nicoya, has the highest amount of fishery activity in the country (Cortés & Wehrtmann, 2009) and is one of the most exploited estuaries in Central America (Herrera-Ulloa et al., 2011). Apart from storm surge protection (Das & Vincent, 2009; Zhang et al., 2012), mangroves also provide additional ecosystem services which include pollution control and also serve as nurseries for diverse group of species (Barbier et al., 2011).

This study shows how the NASA Landsat Archive, which covers over 40 years, can be leveraged to understand changes in landscapes and offers an historical perspective that might otherwise not be available. However, although satellite technology has improved in the last 40 years in terms of spatial and spectral resolution along with increased capture of the electromagnetic spectrum, we had to use a methodology and vegetation index that could be applied to the entire time-series of Landsat images for consistency. Had this study only looked at forest cover change between 1984 and 2014, there would have been a spatial resolution match between the different sensors.

There are a few areas where this study can be improved and expanded. First, looking at how the health of the mangrove has changed over time can help explore what are the effects of increased and upstream industrial agriculture. Second, Landsat 8, which is the newest Landsat satellite launched in 2013, can be used to estimate and track changes in above ground biomass and tree canopy cover (Dube & Mutanga, 2015; Karlson et al., 2015) and could be used to track more recent trends in mangrove health. Additionally, given the spectral overlap between areas of industrial agriculture with other classes, object-based classification may offer a way to avoid manually digitizing those areas. We had to rely on a hybrid classification method that included vegetation index values and on hand digitizing areas with industrial agriculture based on the unique shapes, patterns, and textures associated with this land cover class. Even though the datasets used in the study were freely available, the GIS software used to analyze the data was not. However, the use of freely available software programs such as QGIS (QGIS Development Team; http://www.qgis.org/) and Google Earth Engine (Google Inc., Carnegie Mellon University, NASA, USGS and TIME; https://earthengine.google.com/) is becoming more widespread and the programs more robust, which can help overcome financial barriers encountered by some natural resource and conservation groups.

Overall, the results of this historical study are beneficial to the CBPC Council in aiding them in addressing current environment concerns and in helping with their next strategic plan. For example, they can see the trends in land use change and identify valuable adjacent forest patches that should be monitored and protected from future expansion of industrial agriculture, which is contained in the southeast portion of the CBPC. The maps and data generated from this study will also help guide reforestation efforts throughout the CBPC since these results show areas that have recently undergone deforestation and thus should be considered as areas of concern for future conservation efforts. Based on reforestation trends the Lagarto and Guacimal watershed (Figure 1.1) appear to be good candidates to help link the CBPC. The industrial agricultural expansion has been limited to the southeastern corner of the CBPC.

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CHAPTER 3

EVALUATING THE SPATIAL DISTRIBUTION OF PAYMENT FOR ECOSYSTEM CONTRACTS AWARDED WITHIN THE BELLBIRD BIOLOGICAL CORRIDOR BETWEEN 2008 AND 2012

Introduction

Payment for Ecosystem Services programs are designed to increase incentives to conserve environmental services (Pagiola et al, 2005). These programs act like environmental subsidies and, as such, can incentivize environmentally beneficial activities (Engel et al., 2008). According to Pagiola (2008), the origins of Costa Rica's Payment for Ecosystem Services, known as Pago por Servicios Ambientales (PSA) in Spanish, can be traced to the early 1970s. Concern over diminishing timber supplies led to the creation of tax rebates as incentives for timber plantations. In 1986, The Forest Credit Certificate, known in Spanish as El Certificado de Abono Forestal (CAF), was established to increase participation. In 1995, the Forest Protection Certificate, known in Spanish as Certificado para la Protección del Bosque (CPB), was introduced which supported forest conservation instead of timber productions. Pagiola (2008) posits that the CAF and CPB provided the foundation for Costa Rica's PES program since they provided a system of payments for reforestation and forest management, along with the institutions to manage it.

Costa Rica's PES program was officially authorized with the Forestry Law 7575 in 1996, that limited deforestation even further (Robalino & Pfaff, 2013) and recognized that forest ecosystems provide environmental services such as biodiversity, watershed function, scenic beauty, and greenhouse gas mitigation through carbon storage and sequestration (Daniels et al., 2010). In

1998, the Biodiversity Law 7788 focused on rational use of the biodiversity resources along with their conservation (Sánchez-Azofeifa et al., 2007). The Forestry Law changed the source of financing from the government budget to a designated tax and payments from different beneficiaries (Pagiola, 2008). The PES program is managed by FONAFIFO (Fondo Nacional de Financiamiento Forestal, approx. translation - "National Fund for Forest Financing"). The FONAFIFO program is a semi-autonomous agency with independent legal status that is in charge of channeling government payments to private forestry owners and protected areas (Russo & Candela, 2006).

Evaluating the PES Program

There have been mixed reviews about the effectiveness of the PES program. During the first phase of the PES program, factors such as farm size and household economic level influenced participation in the program resulting in large landowners being disproportionately represented (Sánchez-Azofeifa et al., 2007). Part of the initial bias against poor farmers could result from the fact that working with many small, dispersed farmers imposes high transaction costs since the costs faced by PES programs to contract with participants are based on contract numbers rather than size of farms (Pagiola et al., 2005). Lack of land titles on behalf of poor farmers also excluded them from participating in PSA. However, the law has changed to allow participation of landowners that lack titles (Pagiola, 2008).

Other negative reviews of the PES program stem from utilizing forest cover monitoring and rates of deforestation to evaluate the success the program. A nationwide analysis of the program found no effect of PES on deforestation rates during the initial years (1997-2000) (Robalino & Pfaff, 2013). However, in a farm-level study in the Sarapiquí region, forest cover in farms that participated in PES increased from 11% to 17% (Arriagada et al., 2012). The latter study looked at PES contracts awarded in 1997 and 1998 that were still in effect by 2005.

Tackling deforestation pressure was not the original purpose of the PES program. The PES is, in fact, an instrument for influencing land use in a such a way as to preserve or increase provisions of forest-derived ecosystem services (Daniels et al., 2010). In short, changes in the rate of deforestation may not be an appropriate measure to evaluate PSA. Sánchez-Azofeifa et al. (2007) found that PES contracts may have been targeted in areas where there was a lack of deforestation pressure because the amounts of PES contracts correlated negatively with the 1986-1997 forest clearing.

The authors of the nationwide study of the PES program, Robalino & Pfaff (2013), emphasize the need to target the contracts more effectively in order to have greater impacts. The authors of the farm-level study, Arriagada et al. (2012), speculate that PES implementation in Sarapiquí could have been more targeted and thus more effective, but further research needs to be conducted. Wünscher et al., (2008) found that the PES program could be more efficient if a targeting process that integrates spatial data rather than a targeting system based solely on priority areas (such as the established corridors) was implemented based on their study in the Nicoya Peninsula. The corridors broadly serve as priority regions for PSA, but within those regions there are areas that would have greater impacts than others, i.e., priority areas within the priority areas.

There are currently 37 biological corridors in Costa Rica and they serve as priority areas for the PES since they were created in order to better link protected areas and increase habitat for migratory species and species that require larger home ranges (SINAC, 2009). Additionally, PES areas have been shown to be effective in retaining forest cover and in recruiting tree regrowth within biological corridors in Costa Rica (Morse et al., 2009; Sills et al., 2008). The previous chapter showed an overall increase in forest cover within the El Corredor Biologico Pajaro Campana (CBPC) since 1974. Despite this success, it is critical to evaluate the effectiveness of the PES program within the CBPC; especially since a study within the CBPC examining parcel-level impacts of changes in landscape shows that forest cover is an insufficient proxy for conservation success (Allen & Padgett Vásquez, 2017). Previous studies claim that improving the targeting of PES contracts would improve their effectiveness. Given that forest cover and deforestation rates are not adequate proxies to evaluate the PES program, the goal of this study is to assess the spatial and temporal distribution of the PES contracts that were awarded within the CBPC between 2008 and 2012.

Study Area and Research Goal

The CBPC is delineated East to West by the watersheds of the Aranjuez, Guacimal, and Lagartos Rivers (Figure 3.1). From North to South, the CBPC is delineated by the Monteverde Cloud Forest Reserve at the continental divide to the coastal mangrove forest of the Gulf of Nicoya. FONAFIFO awarded 51 PES contracts within the CBPC between 2008 and 2012. In order to measure the spatial targeting, we evaluated the PES contracts distribution in relation to the Holdridge Life zones included within the CGPC, elevation distribution, distance to rivers, and proximity to protected areas. Additionally, the spatial clustering of the PES distribution was analyzed for each given year. These variables were chosen based on environmental service potential which has been shown to help increase overall financial efficiency of Costa Rica’s PES program (Wünscher et al., 2008).

Figure 3.1 Study Site: El Corredor Biológico Pájaro Campana and its Main Watersheds.

Data Sources and Methodology

A shapefile containing the location and attribute data of the 51 PES contracts within the CBPC that were awarded between 2008 and 2012 was provided by FONAFIFO. The size of the contracts ranged from 11 to 300 hectares. Information concerning Holdridge Life Zones, elevation, rivers, and protected areas were acquired from the 2014 Digital Atlas of Costa Rica (Ortiz Malavassit & Soto Montoya, 2014). These variables for comparison and were analyzed in ArcMAP (v. 10.3, ESRI, Redlands, CA).

In order to determine if the location of PES contracts were clustered around a certain area or dispersed within the corridor, cluster analysis was performed using the Average Nearest Neighbor tool in ArcMAP. The distribution of the PES contracts is considered clustered if the average distance between the PES contracts is less than the average of the hypothetical random distribution (lower than a Z score of -1.96 or 5th percentile). Alternatively, the PES contracts are considered dispersed if the average distance between the PES contracts is more than the hypothetical random distribution (higher than a Z score of 1.96 or 95th percentile). Any value that falls within a Z score of -1.96 and 1.96 (or 5th and 95th percentile) is considered random. The average Nearest Neighbor Ratio is calculated by dividing the observed average distance by the expected average distance.

Results

The PES Contract Locations Relative to Holdridge Life Zones

The CPBC has rich biodiversity with 47% of the reptile species, 51% of bird species, and 48% of mammal species of the country using some portion of the CBPC (Welch et al., 2011). The CBPC contains 11 different Holdridge Life zones, which are land classes based on biological and climatic variables (Holdridge, 1979). Only two of these 11 life zones are not represented in the distribution of the 51 PES contracts awarded by FONAFIFO between 2008-2012 in the CBPC (Figure 3.2). The significance of the area of the two Holdridge Life Zones which are not represented in PES contracts and covers only about 3% of the total area of the CBPC.

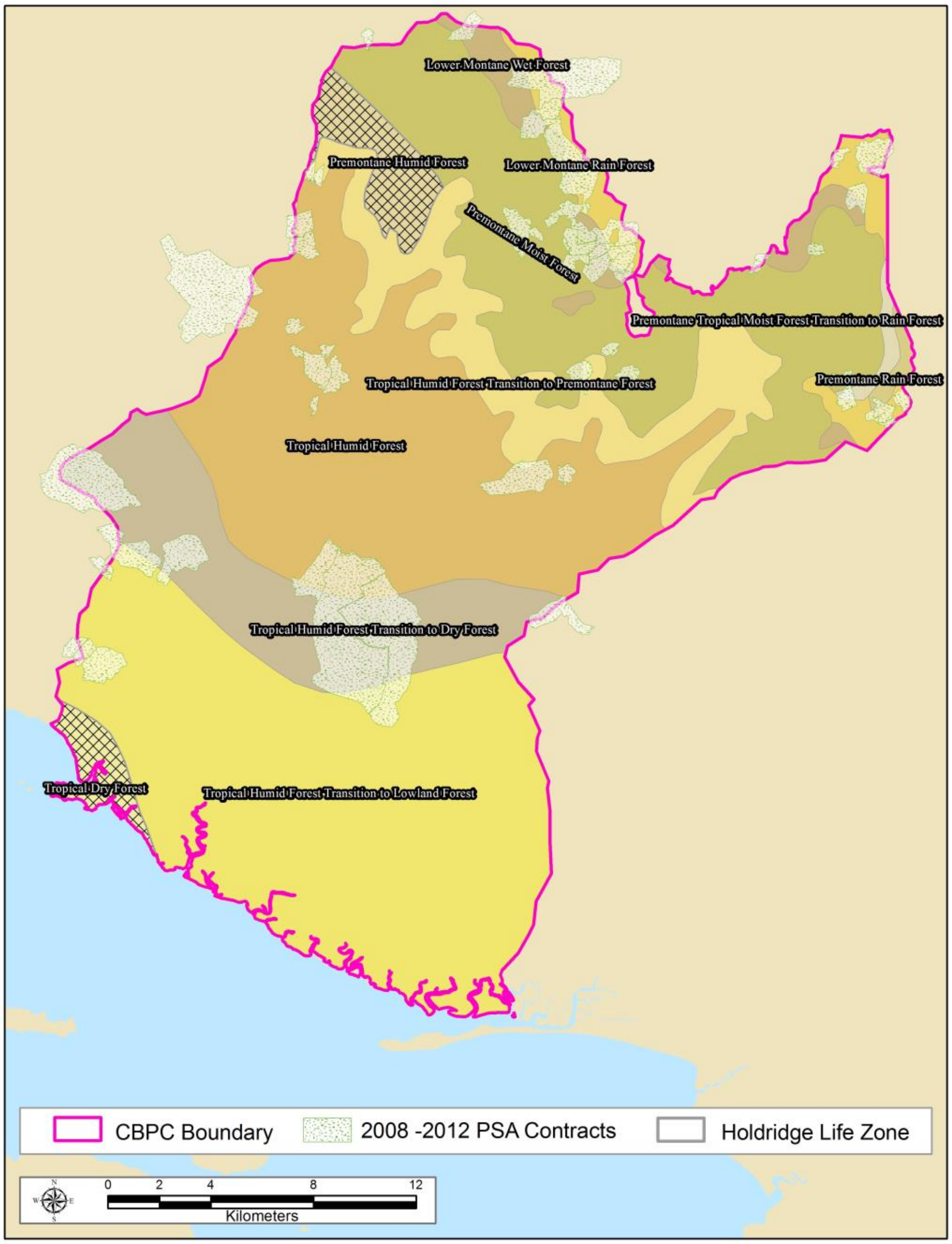

Figure 3.2 2008 -2012 PES Contracts Proximity to Holdridge Life Zones

Elevation

The CBPC has an 1,800-m elevation range with protected areas found at the higher (above 1400m) and the lower elevations (mangroves just above sea level). Close to 73% of the PES contracts (37/51) are located between 100 and 1400 meters of elevation (Figure 3.3). These PES contracts help provide protection of the middle elevation areas, which are particularly underrepresented in the Costa Rica's biological reserves (Powell et al., 2000). Additionally, these middle elevation areas help link the cloud forests with the mangroves.

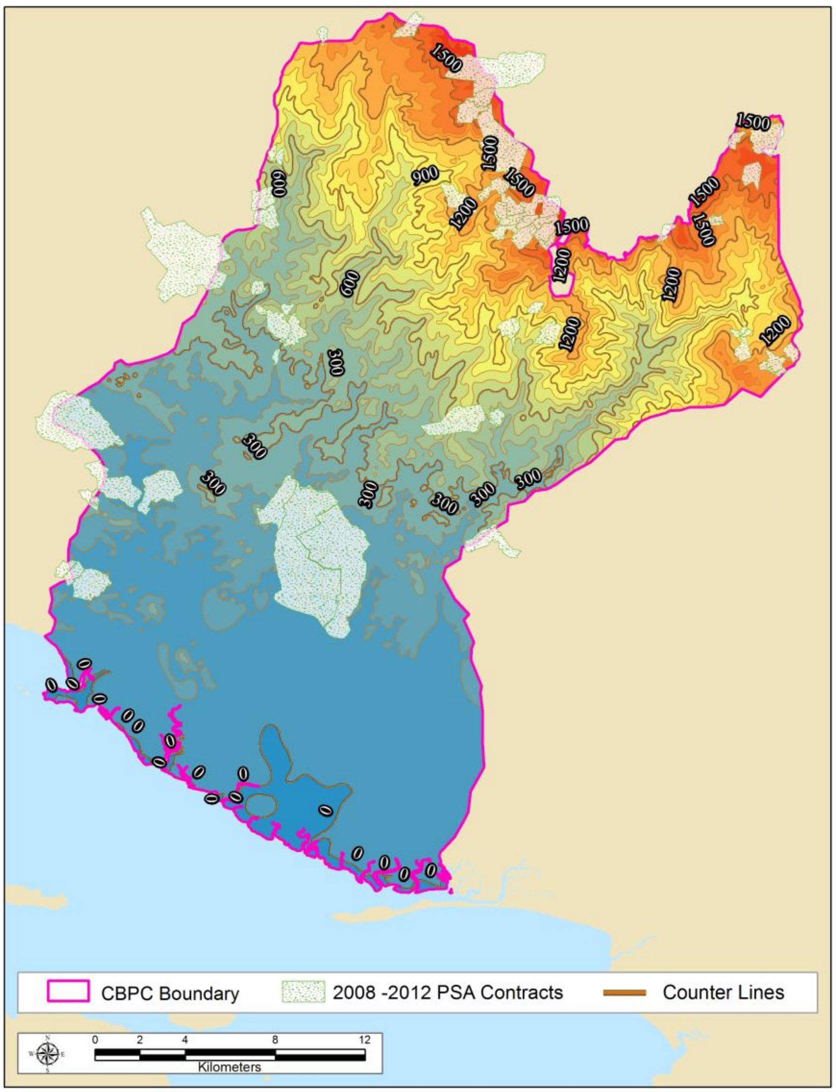

Figure 3.3 2008 -2012 PES Contracts Distribution Across Elevation

Distance to Rivers

The CBPC is biogeophysically defined by the watersheds of the Aranjuez, Guacimal, and Lagartos Rivers and covers approximately 66,400 hectares. Apart from increasing species richness (Sabo et al., 2005), forested areas along streams reduce the input of agricultural nutrients and chemicals to the surface stream waters (Anbumozhi et al., 2005). In Costa Rica, forested river banks have been shown to facilitate the movement of birds in fragmented forest landscapes (Gillies & St. Clair, 2008). Close to 76% of the PES contracts (39/51) include or are within 30m of a river or stream. These PES contracts provide hydro-services and biodiversity services (Figure 3.4).

Figure 3.4 2008 -2012 PES Contracts Proximity to Rivers

Protected Areas

About a fifth (10/51) of PES contracts are within already designated protected areas (Figure 3.5). These PES contracts are located at elevations higher than 1250 meters. One benefit of these areas is that they are located at the head-waters of the three rivers than delineate the CBPC. Since these areas already benefit from a structured conservation focus, the funds could have been better used in different areas if the only goal of the PES was to increase connectivity. However, the Monteverde Reserve uses these funds to run their environmental education program and claim that they would not be able to support without these payments (Méndez, 2009). The benefits of the educational program, though seemingly obvious, would be hard to quantify.

Figure 3.5 2008 -2012 PES Contracts Proximity to Protected Areas

Average Nearest Neighbor Analysis

The Nearest Neighbor Analysis showed that in a given year, the PES contracts were not clustered. In fact, for the years 2008, 2009, 2010, and 2011, the PES contracts were significantly ($p > 0.05$) dispersed (Table 3.1 and Figure 3.6 to 3.9). According to the Nearest Neighbor Analysis, the 2012 PES contracts distribution was random (Figure 3.10).

Table 3.1 Summary of Nearest Neighbor Cluster Analysis

Year PES Awarded	P-Value	Spatial Distribution
2008	0.063	Dispersed
2009	0.014	Dispersed
2010	0.000	Dispersed
2011	0.007	Dispersed
2012	0.939	Random

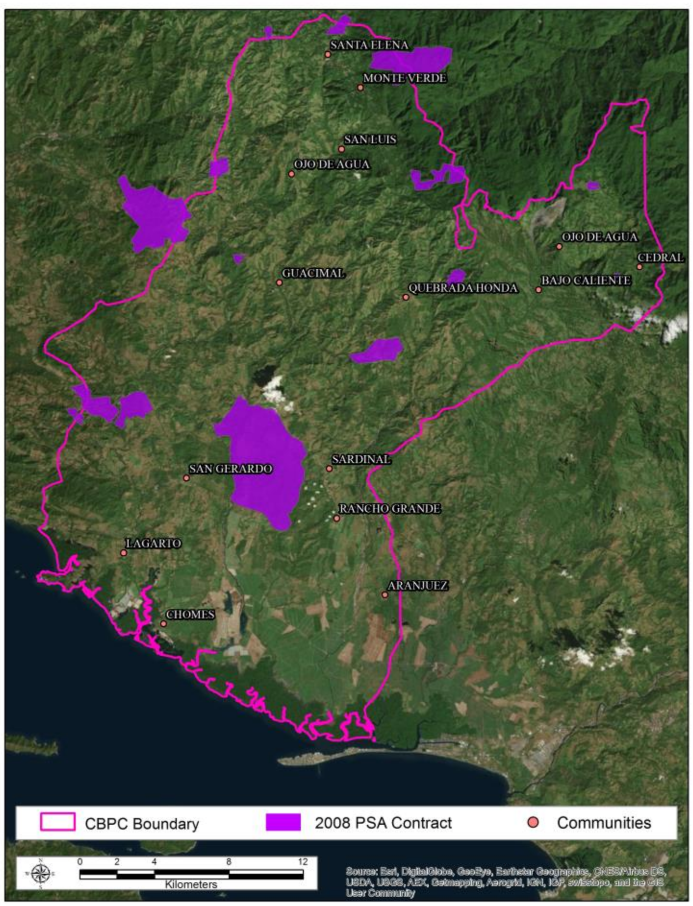

Figure 3.6 Nearest Neighbor Analysis for the 2008 PES Contracts: Dispersed

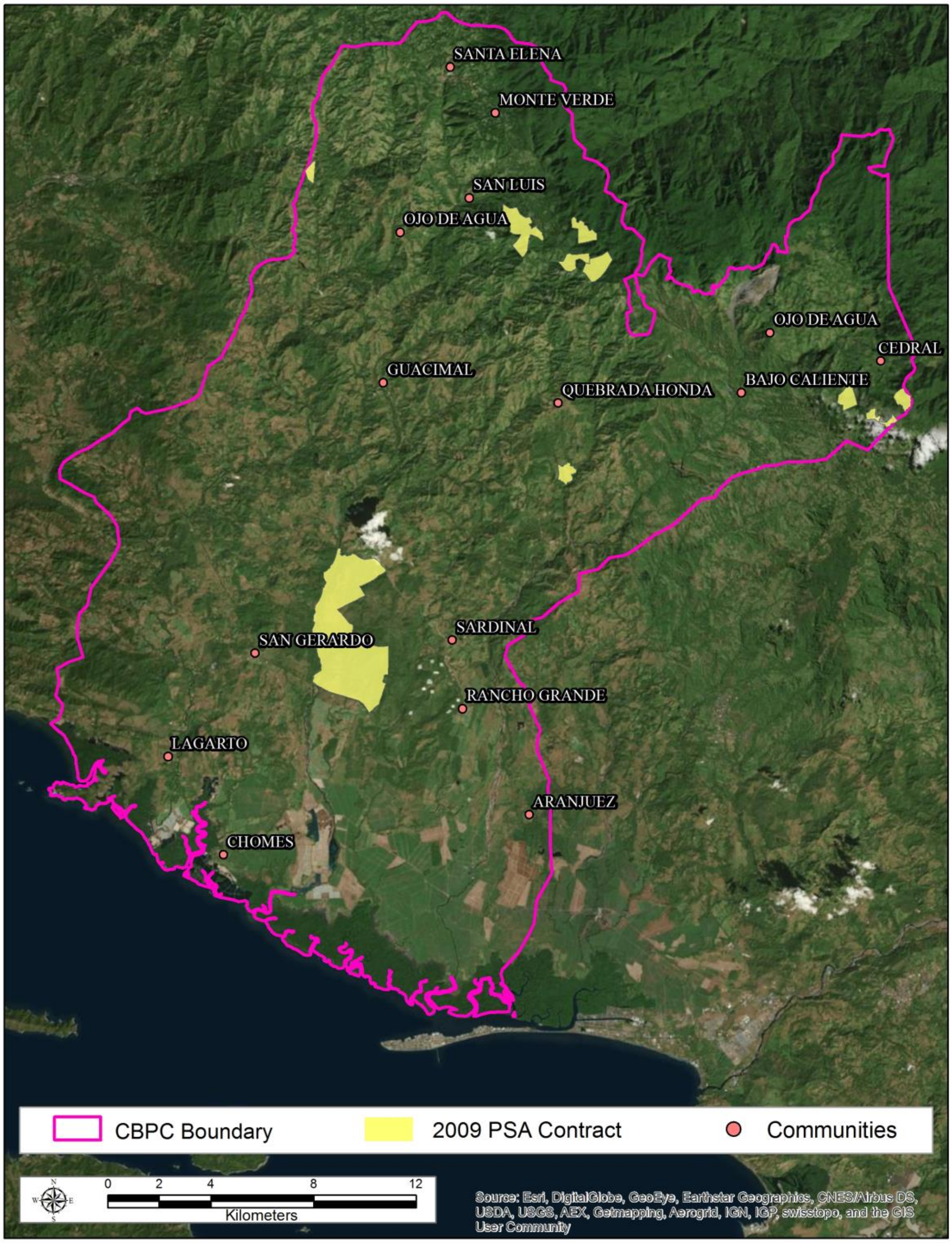

Figure 3.7 Nearest Neighbor Analysis for the 2009 PES Contracts: Dispersed

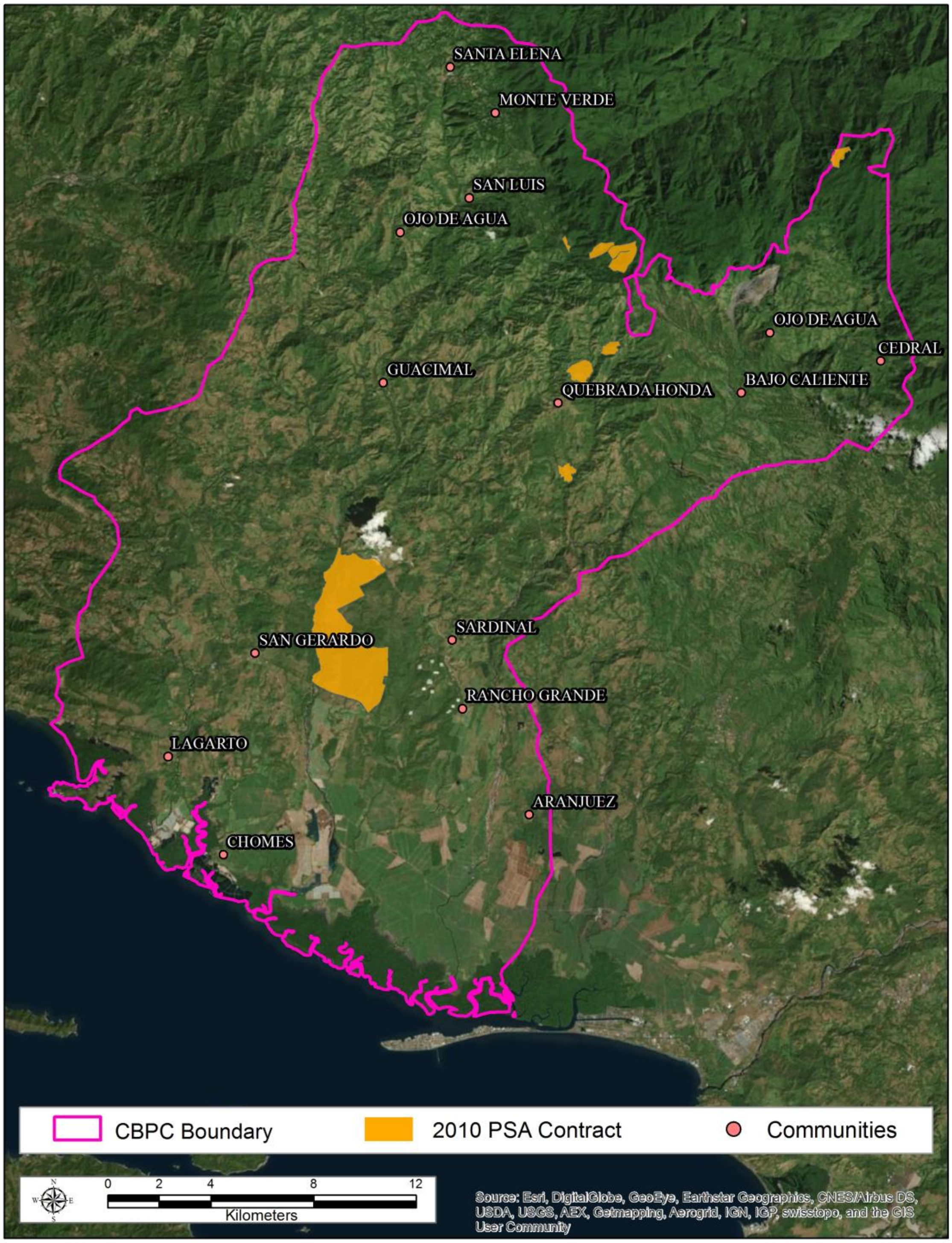

Figure 3.8 Nearest Neighbor Analysis for the 2010 PES Contracts: Dispersed

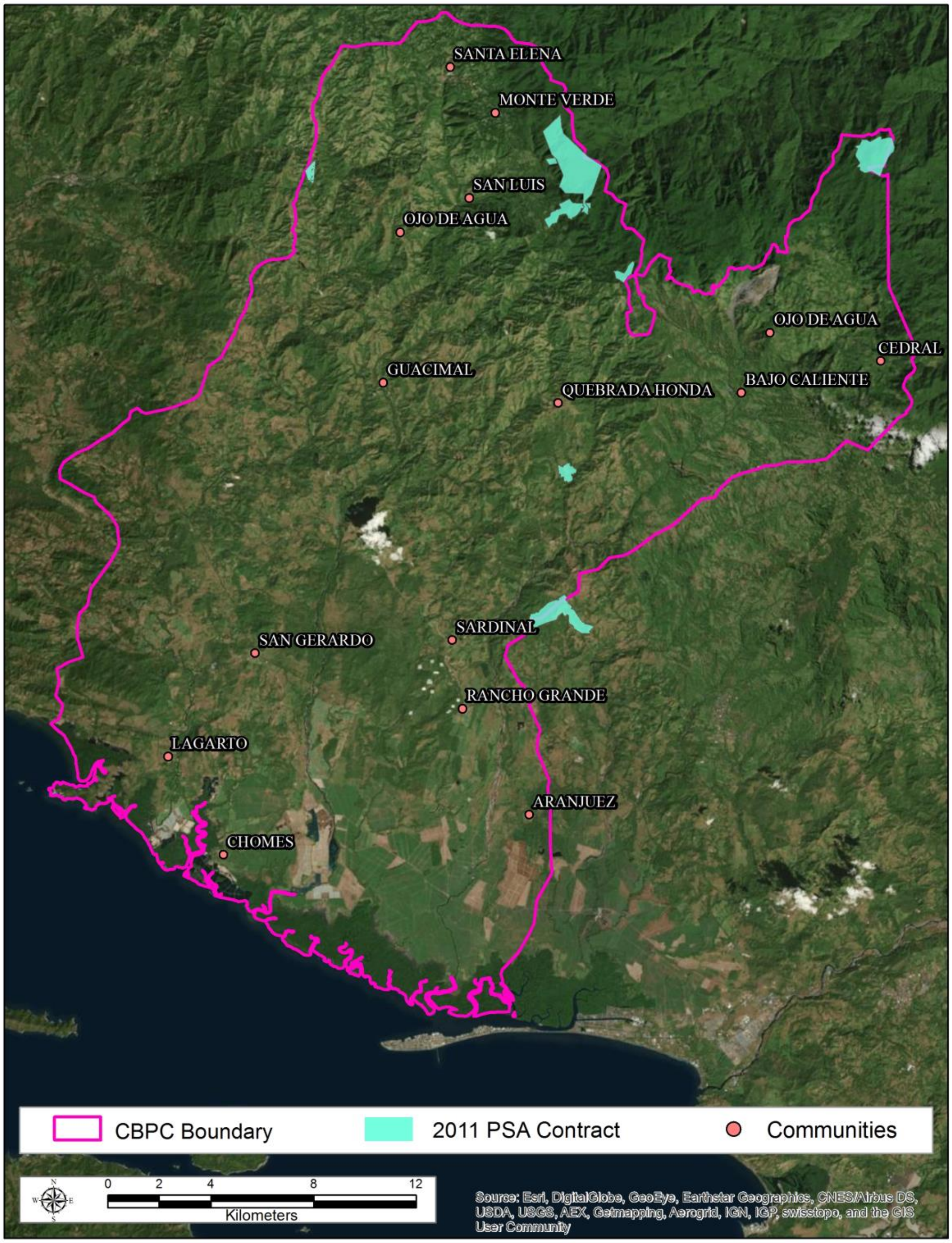

Figure 3.9 Nearest Neighbor Analysis for the 2011 PES Contracts: Dispersed

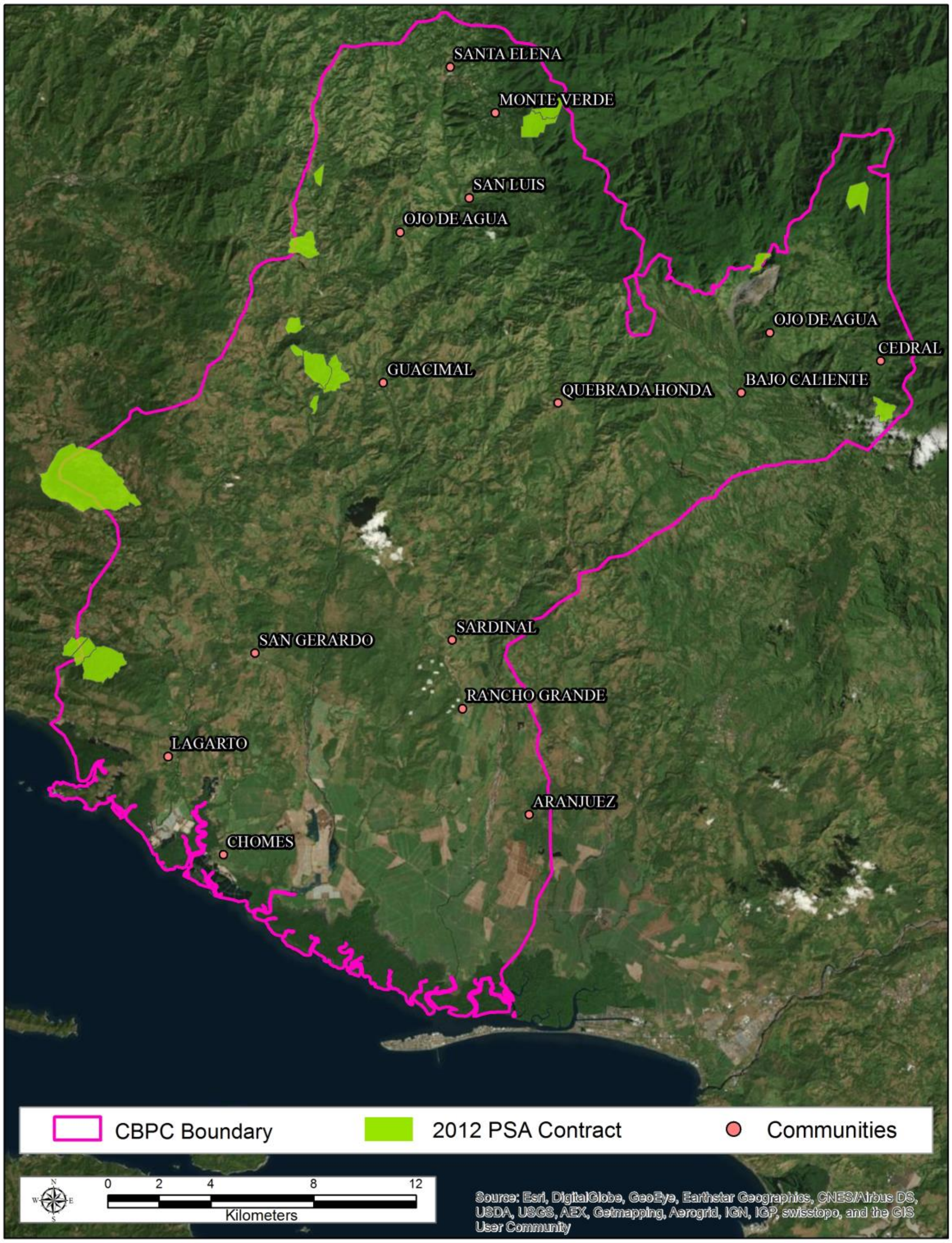

Figure 3.10 Nearest Neighbor Analysis for the 2012 PES Contracts: Random

Discussion

Since forest cover and deforestation rates are not effectives proxies to evaluate the effectiveness of the PES program, the goal of this study was to evaluate the spatial distribution of the PES contracts that were awarded within the CBPC between 2008 and 2012. The Nearest Neighbor analysis revealed that for each individual year, the PES contracts were not clustered within a particular region within the corridor, and consequently spreading the forest protection across the corridor. Additionally, the PES contracts encompass almost all the Holdridge Life Zones and most are found at elevations and areas that are underrepresented in Costa Rica's reserves. Apart from promoting connectivity and forest cover as environmental services, the majority of PES contracts also provide additional environmental services by being located in close proximity to rivers and streams, and thus contribute to the functional integrity of the region's ecosystems. There were two Life Zones that were not represented, but should be areas of priority for future PES contract allocation. The area of the two Holdridge Life Zones that are not represented in PES contracts only covers about 3% of the total area of the CBPC. Additionally, one of the two unrepresented areas is predominately mangroves and remained relatively unchanged since the late 1970s based on the Chapter 2 results.

Overall, the spatial distribution of the PES contracts within the CBPC was positive in the context of facilitating connectivity between the cloud forest and mangroves. One previous study in Northeastern Costa Rica found that targeted PES contracts in the San Juan-La Selva Biological Corridor would protect existing forest connectivity and enhance the connectivity benefits of the reforestation (Fagan et al., 2016). The CBPC serves as priority regions for PSA, but within the corridor there are areas that would have bigger impacts than others. There is a clear need to identify priority areas within corridor in order to increase the effectiveness of future PES contracts and conservation efforts.

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CHAPTER 4

IDENTIFYING PRIORITY AREAS TO PROMOTE FOREST CONNECTIVITY IN THE BELLBIRD BIOLOGICAL CORRIDOR

Introduction

The Advanced Draft of the Connectivity Conservation Area Guidelines (Worboys et al., 2016) claims that connectivity conservation is a direct response to habitat fragmentation as it actively tries to retain and restore natural connectivity in landscapes. One way protected areas can improve their interconnectedness is through corridors, which is defined as connected, linear land areas joining habitats that facilitate animal movement (Singleton & McRae, 2013). Corridors minimize the effects of habitat fragmentation on wildlife (Paul Beier & Noss, 1998) and can facilitate species adaptation to climate change (Carroll et al., 2010; Lawler et al., 2010).

Traditionally, approaches to connectivity have been divided into two categories. When connectivity is based on species behavior it is often described as functional connectivity, while connectivity based entirely on landscape structure is called structural connectivity (Kindlmann & Burel, 2008). However, what these two approaches fail to consider is that corridors are often facilitated through a number of legal tools and policy instruments that cover a spectrum from direct regulations to voluntary agreements (Worboys et al., 2016). Successful corridor design and management focuses on implementing linkages in a landscape through purchasing and/or protecting areas since spatially explicit connections are necessary (Krosby et al., 2015).

Corridor modeling has traditionally relied on a focal species approach, which builds upon the concept of the umbrella species whose requirements are believe to include the needs of other species (Lambeck, 1997). Results have been mixed about the use of a single species focused model and the use of multiple focal species is recommended when creating a corridor design (Beier et al., 2008). At broad scales, focal species connectivity modeling becomes difficult since large numbers of focal species may be required to represent the different habitat types and it would also require months or years, along with substantial financial cost (Beieret al., 2011; Krosby et al., 2015).

Krosby et al. (2015) compared the results of running a species focus model (measuring functional connectivity) with the results of a naturalness-based corridor model (measuring structural connectivity) and found that naturalness-based corridors may offer an efficient proxy for species models, especially in the case of limited or non-existing species movement data. The study had movement data on 12 animal species. A single naturalness-based corridor model was as effective as a group of four randomly selected focal species (from the 12) for the same area. After more than five randomly focal species used, the single naturalness-based model was no longer as effective. The authors point out that a multi-focal species approach may better represent the movement needs of diverse taxa. Baldwin et al. (2010) have similar suggestions about modeling corridors, where a “naturalness” approach can be beneficial, especially when the focal species modeling is over a broad area and heterogeneous landscape.

Corridor modeling facilitated by GIS and least-cost analysis is at the core of most current approaches to corridor design (Beier et al., 2008). Least-cost modeling is used to measure the cost for an organism to move between patches based on information about the landscape, along with behavioral aspects of organisms studied (Adriaensen et al., 2003). A least-cost path, as the name suggests, is the shortest ecological distance between two patches. The least-cost path is calculated from a cost/priority surface, which is the base of the modeling process were areas are assigned cost/priority values that represent varying degrees of structural and functional connectivity (Wade, McKelvey et al., 2015). Apart from structural and functional connectivity factors, incorporating the available legal instruments and tools that already exist in many legal systems would also help promote and implement science-based connectivity (Lausche et al., 2013).

Study Area and Research Goal

El Corredor Biológico Pájaro Campana (CBPC) is a designated conservation area in Costa Rica that aims to bridge the cloud forests of the central mountainous Monteverde region with the coastal mangroves. Once the CBPC was established in the mid-1990s, initial conservation goals involved planting native tree species along riparian areas and along current forested areas in order to promote forest cover and connectivity (Welch et al., 2011). The CBPC is not a true corridor since it is does not provide a connected, linear land between the cloud forests and the mangroves. The boundaries of the CBPC are not based on empirical or speculated animal movement data, but on watershed delineations, as described in Chapter 3 Figure 3.1.

The overall goal of this research is to identify areas for reforestation within the CBPC that would improve connectivity while leveraging laws and policies that would facilitate connectivity conservation. Since there is limited animal movement data available for the entire CBPC but is mostly focused on the Monteverde region, this study took a naturalness approach to corridor modeling. Noting both the amount of the forest that remains and its distribution influence the conservation of the area (Daily et al., 2003), it is important to identify those key areas of ecological function that will improve its connectivity. The results of this study benefit local conservation efforts by determining priority areas for reforestation and conservation efforts, including the reforestation program at the UGA Costa Rica Campus, future PES contract allocation FONAFIFO, and the greater CBPC Initiative.

Methodology

Forested areas measuring over 1.4 km^2 were identified as source areas to be connected in order promote forest connectivity. The resulting eleven forested areas were spread across the corridor (Figure 4.1) and potential linkages between these areas were derived using Linkage Mapper Connectivity Analysis Software (The Nature Conservancy, Seattle, Washington, USA http://www.circuitscape.org/linkagemapper) and the methodology developed by McRae & Kavanagh (2011). Linkage Mapper uses network theory in order to estimate connectivity and potential corridors among habitats (Nordén, 2016). There are many software packages and plug-ins that can be used for wildlife corridor design and management. Linkage Mapper was the best option given the available geospatial data and the lack of species movement data for the entire study area. Another influencing factor for using Linkage Mapper was the ease of use for local stakeholders. For example, rerunning the model with different parameters can be done simply by updated a Microsoft Excel spreadsheet. Additionally, there is an active and friendly Google group that can support anyone using the software. Finally, as more data become available, these data can easily be incorporated into the model.

We ran the tool using cost-weight distance for the network adjacency and set the number of connected nearest neighbor to four, which is the most the model will allow, and shows all potential linkages between sources areas. The Gnarly Landscape Utilities (The Nature Conservancy, Fort Collins, CO, USA http://www.circuitscape.org/gnarly-landscape-utilities) and the methodology developed by McRae, Shirk, & Platt (2013) were used to generate resistance layers, which are layers created to show the cost or barrier between two points of interest. I used the defaults of the model, with the exception of the resistance calculation method, which used the sum option to show the cumulative effects of all resistance layers. This was done because it is a more appropriate measure of connectivity between locations since it factors the distance traveled and cost traversed (Etherington & Holland, 2013).

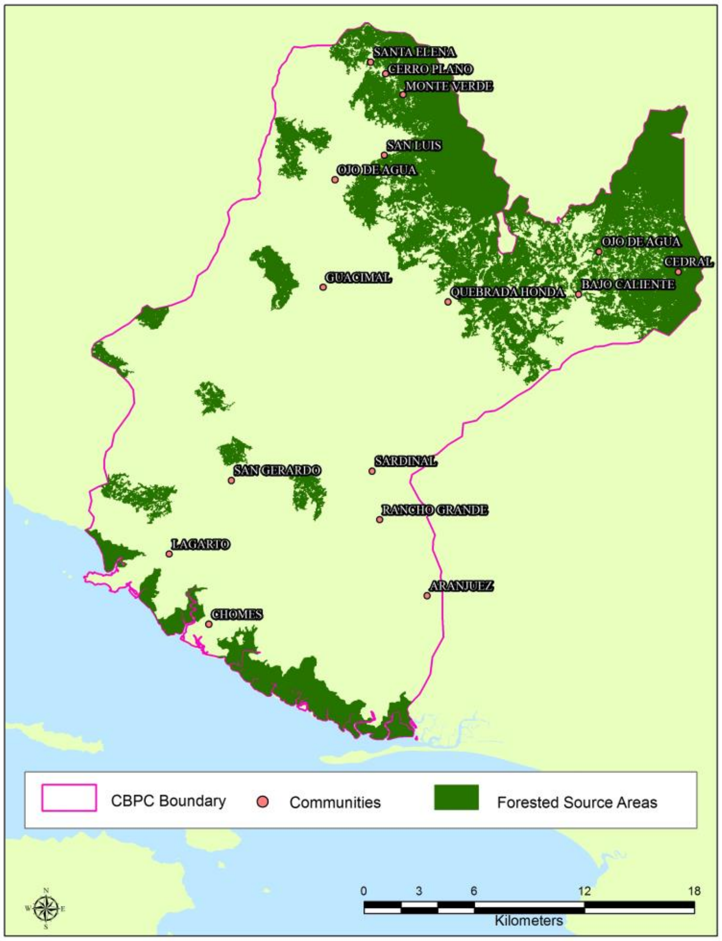

Figure 4.1 Calculated Forest Source Areas to be Used in the Corridor Model

The resistance layers help to determine the path of least cost or friction (and higher priority) between two sources, in our case, between forested areas. Based on feedback from members of the CBPC Council, resistance layers for land cover, elevation, slope, rivers, roads, protected areas, and areas awarded payment for ecosystem services contracts were generated. Since members of the CBPC will build upon this work, it was important to create a model based on factors that they believed were important and that could be backed up by scientific research. Given the lack of species movement data across the entire CBPC, assessing the functional connectivity of the CBPC was not an option. In order to assess the structural connectivity, the following factors were chosen to help determine linkages between the 11 core areas: land cover, elevation, slope, roads, protected areas, rivers, and payment for ecosystem service contract areas. The last two factors allowed us to incorporate laws and policies that could be leveraged in order to facilitate forest connectivity.

The land cover data were derived from the results of Chapter 2. The payment for ecosystem services contract locations were provided by FONAFIFO, the governing body of the Payment for Ecosystem Services Program (Pago por Servicios Ambientales). The remaining variables were derived from the 2014 Digital Atlas of Costa Rica (Ortiz Malavassit & Soto Montoya, 2014), a publicly available geodatabase created by the Instituto Tecnológico de Costa Rica (TEC). A summary of the model layers generated, their resistance class values, and their source is provided in Table 4.1. Details of how resistance values were assigned are provided here.

Table 4.1 Summary of Parameters of Weighted Corridor Variables for Linkage Mapper Based on Stakeholder Feedback

Data Layer	Class Description	Source	Resistance
Elevation	0-200m	DEM	10
Elevation	200-400m	DEM	10
Elevation	400-600m	DEM	0
Elevation	600-800m	DEM	0
Elevation	800-1000m	DEM	0
Elevation	1000-1200m	DEM	0
Elevation	1200-1400m	DEM	0
Elevation	1400-1600m	DEM	0
Elevation	1600-1800m	DEM	20
Elevation	1800-2000m	DEM	20
Land Cover	Non-Forested	From Chapter 2 Results	40
Land Cover	Forest	From Chapter 2 Results	0
Land Cover	Mangrove	From Chapter 2 Results	0
Land Cover	Industrial Agriculture	From Chapter 2 Results	60
Land Cover	Aquaculture	From Chapter 2 Results	80
Rivers	Null	CR Atlas 2014 and DEM	10
Rivers	Steep Slope >15 deg 50m Buffer	CR Atlas 2014 and DEM	0
Rivers	Flat < 15 deg 15m Buffer	CR Atlas 2014 and DEM	0
Roads	Null	CR Atlas 2014	0
Roads	Local 10m	CR Atlas 2014	10
Roads	Trail 10 m	CR Atlas 2014	10
Roads	Tertiary 20m	CR Atlas 2014	40
Roads	Secondary 20m	CR Atlas 2014	60
Roads	Primary (Pan-American HWY) 30m	CR Atlas 2014	80
Payment for Ecosystem Services	Contract Area	From FONAFIFO 2008-2012	10
Payment for Ecosystem Services	Non-Contract Area	From FONAFIFO 2008-2012	0
Protected Areas	Non-Protected Area	CR Atlas 2014	10
Protected Areas	Protected Area	CR Atlas 2014	0
Slope	0 to 5 Degrees (Natural Breaks)	DEM	0
Slope	6 to 12 Degrees (Natural Breaks)	DEM	0
Slope	13 to 19 Degrees (Natural Breaks)	DEM	5
Slope	20 to 26 Degrees (Natural Breaks)	DEM	10
Slope	27 to 34 Degrees (Natural Breaks)	DEM	20
Slope	35 to 58 Degrees (Natural Breaks)	DEM	30

Elevation

The protected areas within the CBPC are found at the highest and the lowest elevations including the cloud forests at above 1,400 m and mangroves at sea level. The middle elevation areas are particularly underrepresented in the Costa Rica's biological reserves (Powell et al., 2000). Additionally, a study by Kohlmann et al. (2010) identified tropical wet forests in the northeastern lowlands (including the CBPC) as one of three most important conservation areas in the country. This area is found in the middle elevations of the CBPC. A resistance layer was generated in ArcGIS based on 200-m elevation increments; between 0 m and 2,000 m (Figure 4.2). Pixels above 1,600 m were given a resistance value of 20 since the least deforestation has occurred at the highest elevations. A resistance value of 10 was given to pixels below 400 m, which include mangroves and protected areas within the CBPC. For the remaining pixels of elevations between 400 m and 1600 m, a resistance value of 0 was assigned since these areas require more representation in conservation efforts and they are more fragmented.

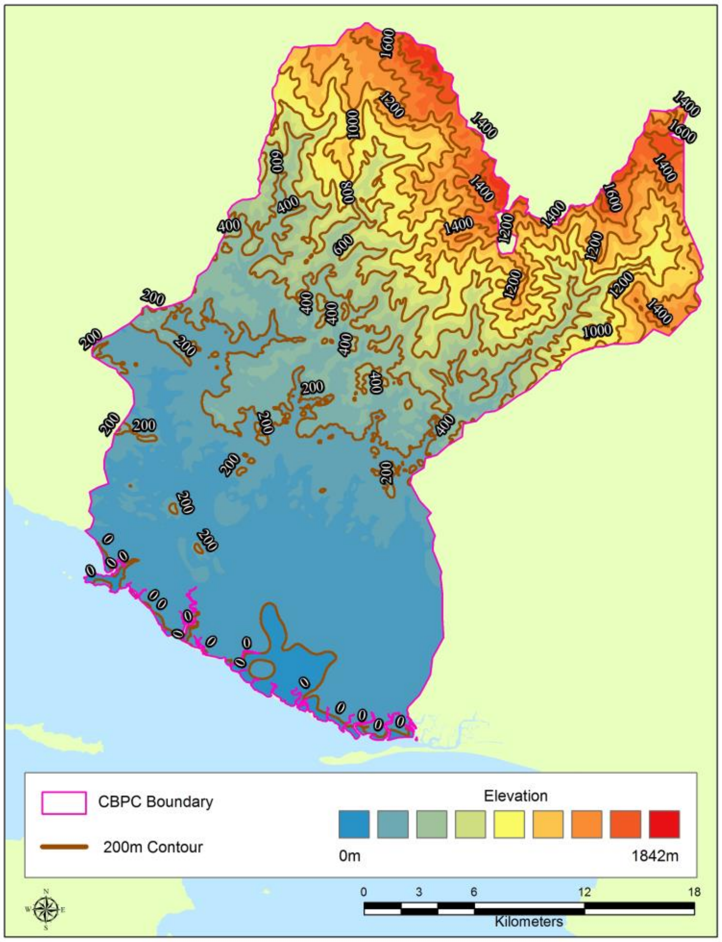

Figure 4.2 200-m Contour Elevation Distribution across the CBPC

Land Cover

A land cover resistance layer that focused on current tree cover within the corridor also was generated. Areas with grasslands and agriculture in Costa Rica have lower species richness than forests (Daily et al., 2003) and studies have shown pasture and agriculture avoidance by frogs (Nowakowski et al., 2013) and birds (Hadley & Betts, 2009; Lindell et al., 2004). Even though some animals can move across a non-forested landscape, pastures and agricultural areas can have negative effects at different stages of an animal's lifecycle. For example, white-throated robin (*Turdus assimis*) fledglings have an increased likelihood of dying in non-forested areas in

Costa Rica (Cohen et al., 2004). Identifying the current tree coverage of the corridor was important since single trees and windbreaks can facilitate animal movement and reforestation within the Monteverde region (Harvey, 2000).

The 2014 land cover data derived from Chapter 2 was used to derive the land cover resistance layers with the following classes: Forested, Non-Forested, Marsh, Aquaculture, and Industrial Agriculture (Figure 4.3). Non-Forested areas included pastures, riverbanks, towns, and fine-scale agricultural farms. One of the largest towns, Santa Elena near the Monteverde Cloud Forest Reserve, has a population of 8,000 (Haber et al., 2000). Due to the low population density and lack of large cities, towns were grouped under the Non-Forested class. Industrial agricultural areas included broad-scale farming. The resistance values for Forested and Mangrove areas were zero, since these are the land cover areas that conservation efforts want to promote. Non-Forested areas were given a resistance of 40 since these areas are mostly pastures. Areas classified as Industrial Agriculture were assigned a resistance of 60 since monoculture cropping areas are less likely than pastures to revert back to natural vegetation. Areas classified as aquaculture were assigned a resistance of 80 since these areas are not naturally occurring and limited natural habitat value to local organisms.

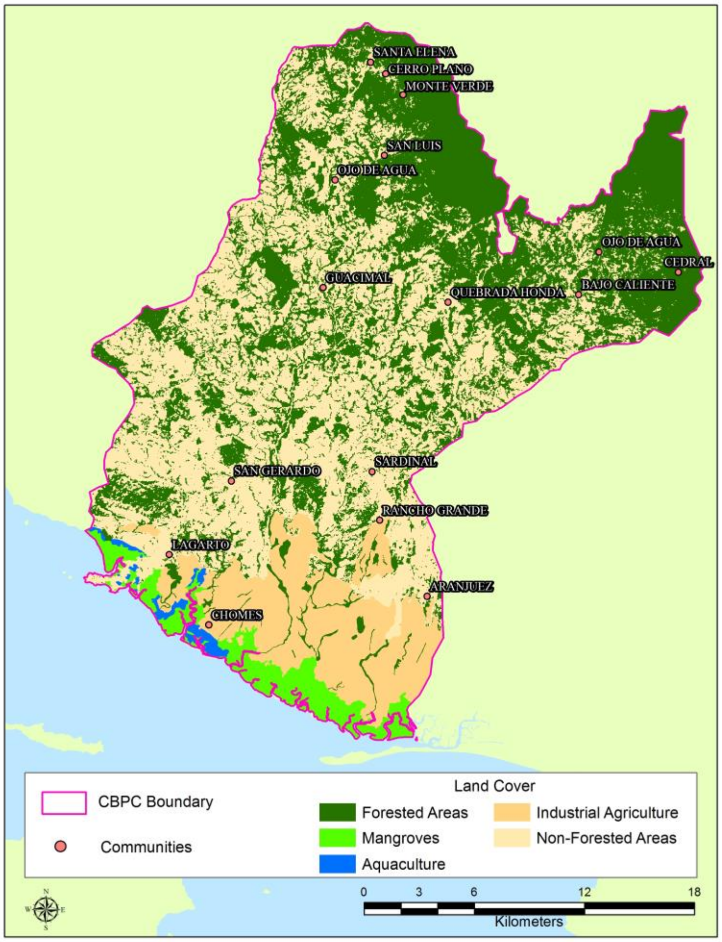

Figure 4.3 2014 Land Cover Map of the CBPC

Protected Areas

The protected areas within the CBPC are both government and privately owned and are found at the highest elevations in the cloud forest and the lowest elevations along the coast and among the mangroves. Protected areas depend on surrounding landscapes in order to maintain the flow of organisms, nutrients, and water resulting in a zone of interaction that is much greater than the protected area itself (DeFries et al., 2010). In order to prioritize conservation areas closer to protected areas, a 1-km ring buffer, up to 10-km buffer, was created around these protected areas (Figure 4.4). The resistance/cost increased in the 1-km buffers the farther away they were from the protected areas

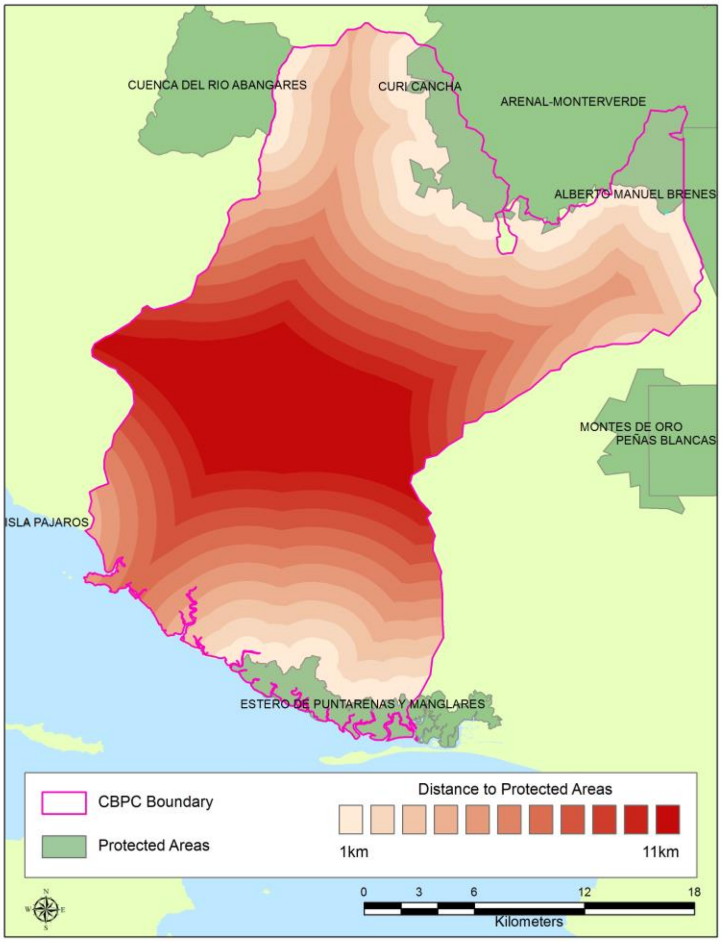

Figure 4.4 Calculated Distances from Protected Areas

Rivers

According to the Connectivity Conservation Area Guidelines Advanced Draft created by the IUCN (International Union for Conservation of Nature), a corridor can only be as healthy as its neighboring waters (Worboys et al., 2016). Forested areas along streams help reduce the influence of agricultural nutrients and chemical on surface stream waters (Anbumozhi et al., 2005) and can also increase species richness (Sabo et al., 2005). In Costa Rica, studies have shown that riparian buffers facilitate the movement of birds in fragmented forest landscapes (Gillies & St. Clair, 2008) and reduce the impacts of deforestation on benthic macroinvertebrates (Lorion & Kennedy, 2009). Buffers along streams were generated based on the Costa Rican Riparian Law (Ley 7575, Chapter IV, Article 33). In areas with low slopes (less than 15 degrees), the law requires a 15-m buffer. In areas with steeper slope (more than 15 degrees), the law requires a 50-m buffer (Figure 4.5). A raster layer of buffered streams within the CBPC was created with stream buffers having a resistance value of 0. The rest of the pixels received a resistance value of 10 in order to promote conservation along riparian areas.

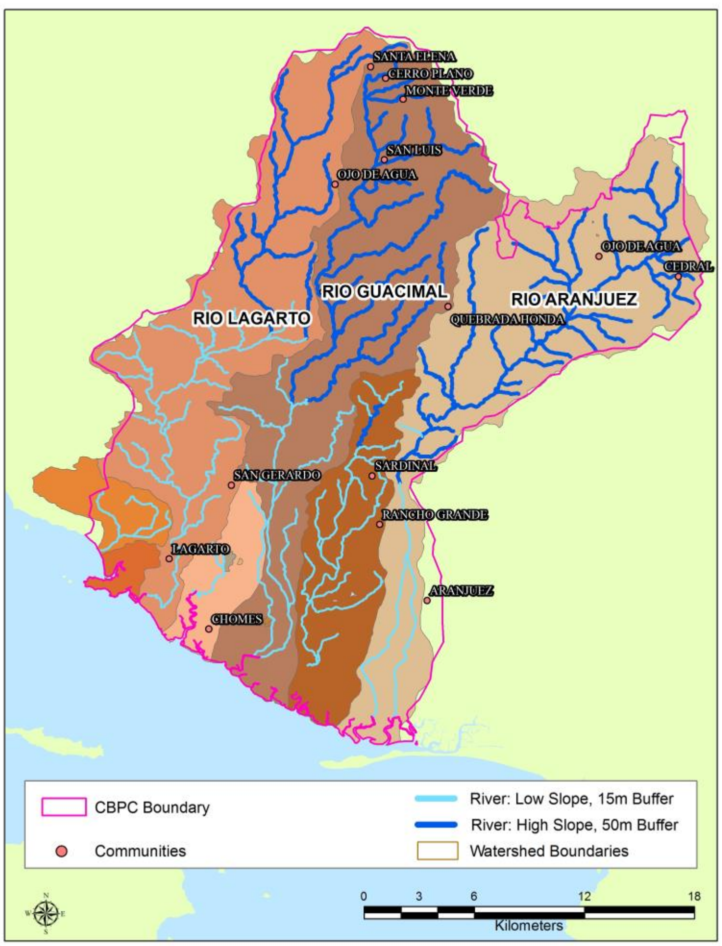

Figure 4.5 Major Rivers and Watersheds of the CBPC

Roads

Roads serve as barriers in animal movement. Studies have shown road avoidance by large mammals (Whittington et al., 2004), small mammals (Rico et al., 2007), and reptiles (Shepard et al., 2008). The width of roads, more than amount of traffic, affects the degree of avoidance of small mammals (Rico et al., 2007). Buffers along roads were created based on the categories provided by the 2014 Digital Atlas in order to generate a raster layer of road buffer resistance. Pixels that were outside the buffer areas were given a resistance value of 0. A 30-m buffer was created around the Pan-American Highway, which is the widest and busiest road in the corridor. Pixels within this buffer received a resistance value of 80. For secondary roads a 20-m buffer was generated with a resistance value of 60. For tertiary roads, a 20-m buffer was generated with a resistance value of 40. Finally, a 10-m buffer with a resistance value of 10 was generated for trails and minor roads (Figure 4.6). The majority of these roads are paved and the classification was based on usage.

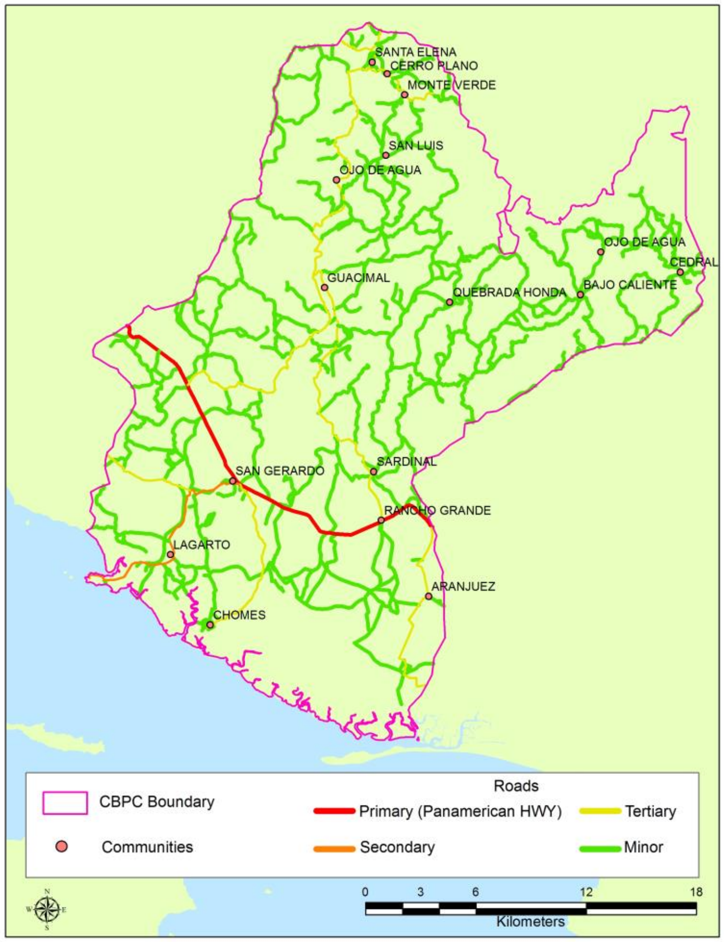

Figure 4.6 Road Network of the CBPC

Slope

A 30-m digital elevation model, provided by the 2014 Digital Atlas of Costa Rica, was used to calculate slope. A slope resistance layer was created based on the natural breaks of the digital elevation model that resulted in 6 classes (Figure 4.7). Higher resistance values were given to steeper slopes, since these areas in Costa Rica have been associated with lower deforestation rates and increase the likelihood of having forest cover (Robalino & Pfaff, 2012; Sánchez-Azofeifa et al., 2007). Table 4.1 summarizes the various slope classes and their respective resistance values.

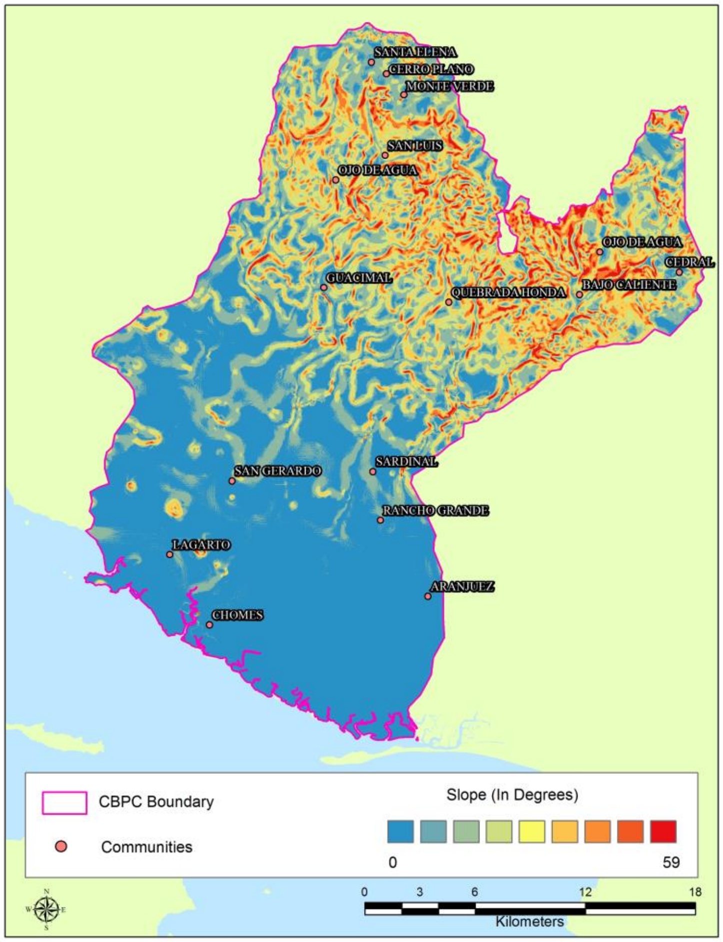

Figure 4.7 Slope Distribution of the CBPC

Payment for Ecosystem Services Contracts

In 1998, Costa Rica established its Payment for Ecosystem Services ("Pago por Servicies Ambientales" or PSA) which provides compensation to people who possess forest land that provides some particular environmental service including climate-change-mitigation services, hydro services, scenic services and biodiversity services (Robalino & Pfaff, 2013). The PES contracts designed to increase incentives to conserve environmental services by capturing the benefits derived from environmental services and directing them to natural resources managers that generate them (Pagiola et al., 2005). PES acts like an environmental subsidy and as such, can incentivize environmentally beneficial activities (Engel et al., 2008). (For more information on the PES program, please see Chapter 1.) Given that the length of PES contracts is for 15 years and they carry a restriction on the land title so that the contract carries over should the land be sold, (Pagiola, 2008), any PES areas would have a legal framework and incentive to participate in forest conservation. A binary raster layer was created of the locations of the 51 PES contracts that were awarded between 2008 and 2012 (Figure 4.8). Pixels that were outside of PES contract areas were assigned a resistance value of 10. In order to promote areas that were awarded PES contracts, pixels that were inside PES contract areas were assigned a resistance value of 0 since PES areas have been shown to be effective in retaining forest cover and in recruiting tree cover within biological corridors in Costa Rica (Morse et al., 2009; Sills et al., 2008).

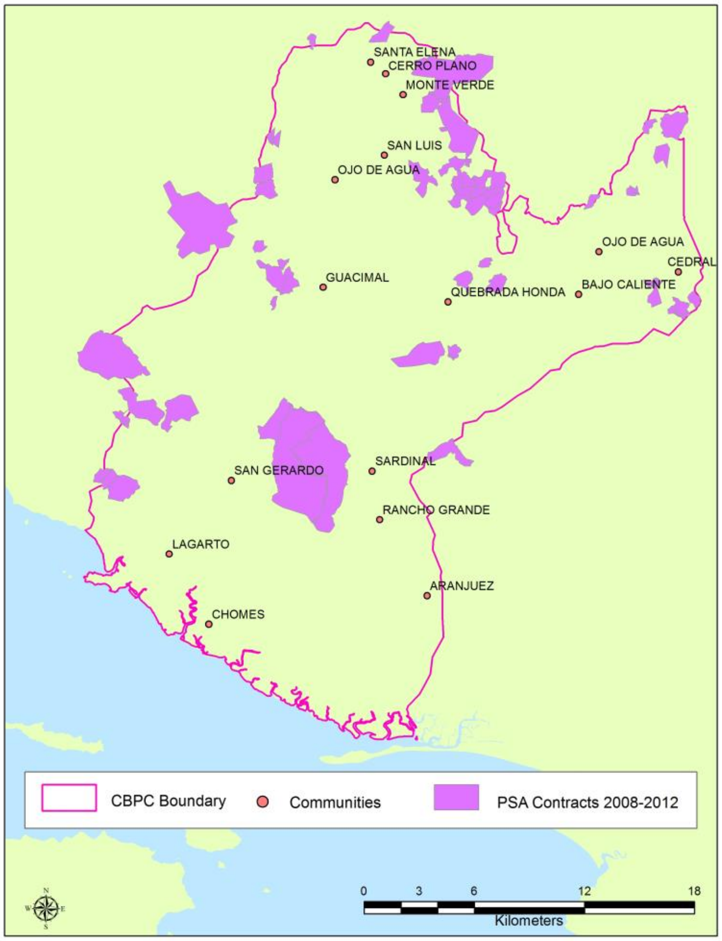

Figure 4.8 2008-2012 PES Contract Distribution Within the CBPC

Results

The outputs of the Linkage Mapper model include a cumulative least cost path and a raster layer showing the total resistance for each cell within the CBPC. The least cost path is a hypothetical line that connects two source polygons, in this case two forested areas, based on weighted variables. The least cost path connects two forested areas in a route that encounters the least amount of resistance and is therefore more likely to promote forest connectivity. The raster layer generated by the Linkage Mapper model is the sum value of all the weighted resistance variables for a given cell. Lower cumulative resistance indicates areas of higher priority based on our variables. The results of the Linkage Mapper model are visualized in Figures 4.9a and 4.9b.

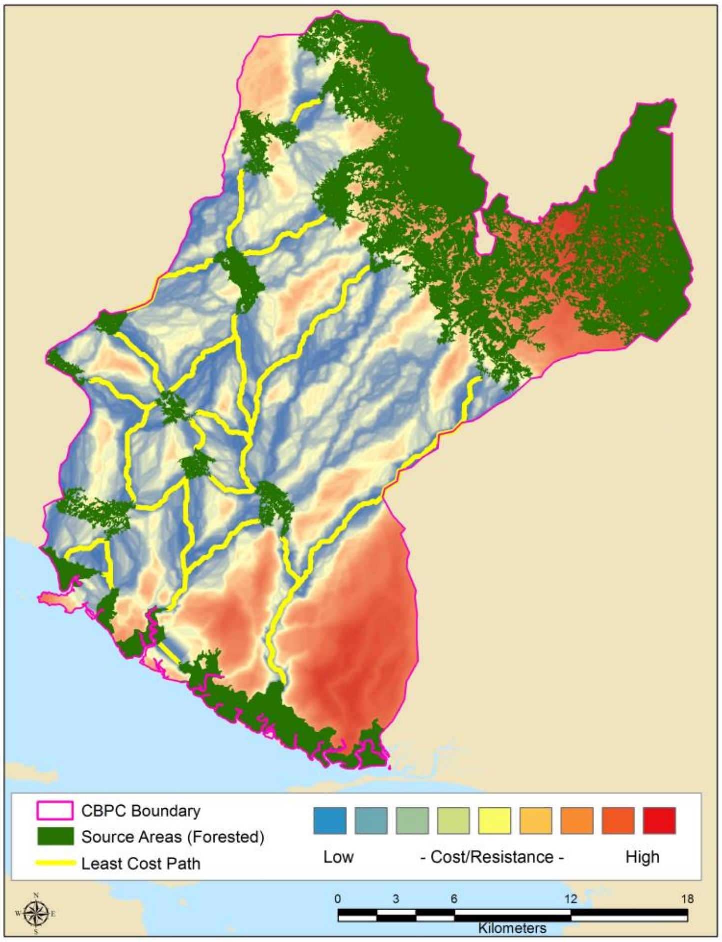

Figure 4.9a Linkage Mapper Results. The resistance/cost between the forested source areas were calculated along with their least cost paths.

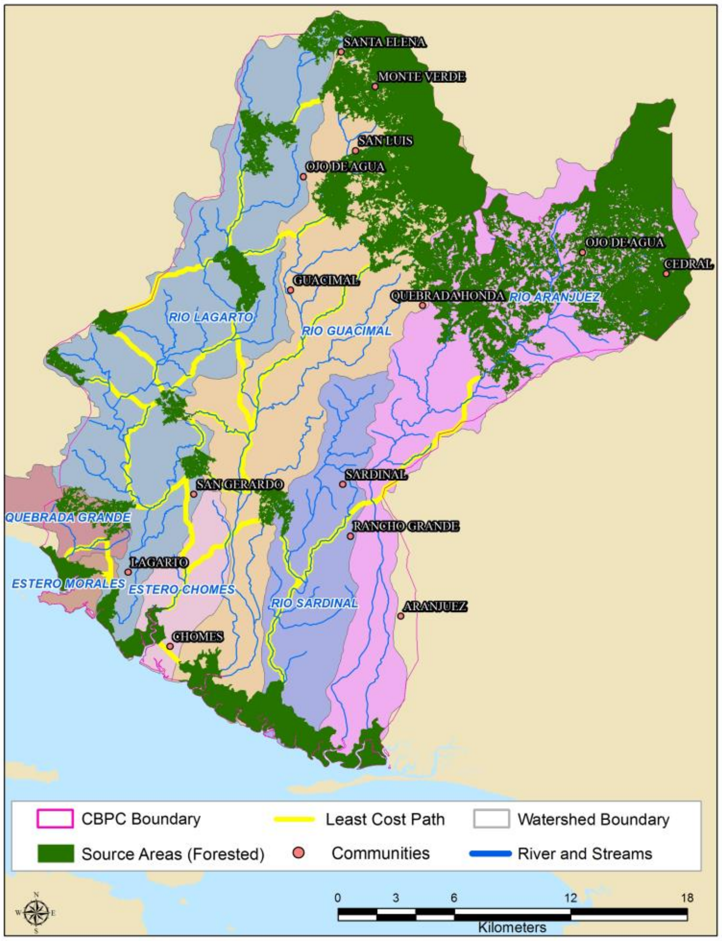

Figure 4.9b Linkage Mapper Results Overlaid on Watersheds Found within the CBPC. The least cost paths results overlaid on the watersheds found within the CBPC.

Sensitivity Analysis

According to Adriaensen et al., (2003), resistance/cost values serve as a link between species ecology and GIS. It is common practice to use expert opinion to determine what values to use and be quite useful in corridor design, especially when observational data are not available (Clevenger et al., 2002). However, the use of expert opinion introduces uncertainty into a corridor model (Beier et al., 2008). In order to evaluate the effects of the resistance/cost values on the results, a jackknife sensitivity analysis, also known as a one-factor-at-a-time sensitivity analysis, was performed. The model was implemented seven times. In each case one parameter was removed and all remaining parameters remained the same (Figure 4.10 - Figure 4.16). McRae and Kavanagh (2011) recommend running the model multiple times under different parameters to help understand the influence of each variable on the spatial distribution of the model. The resulting least cost paths from each run from the sensitivity analysis were superimposed over each other to reveal areas of overlap (Figure 4.17)

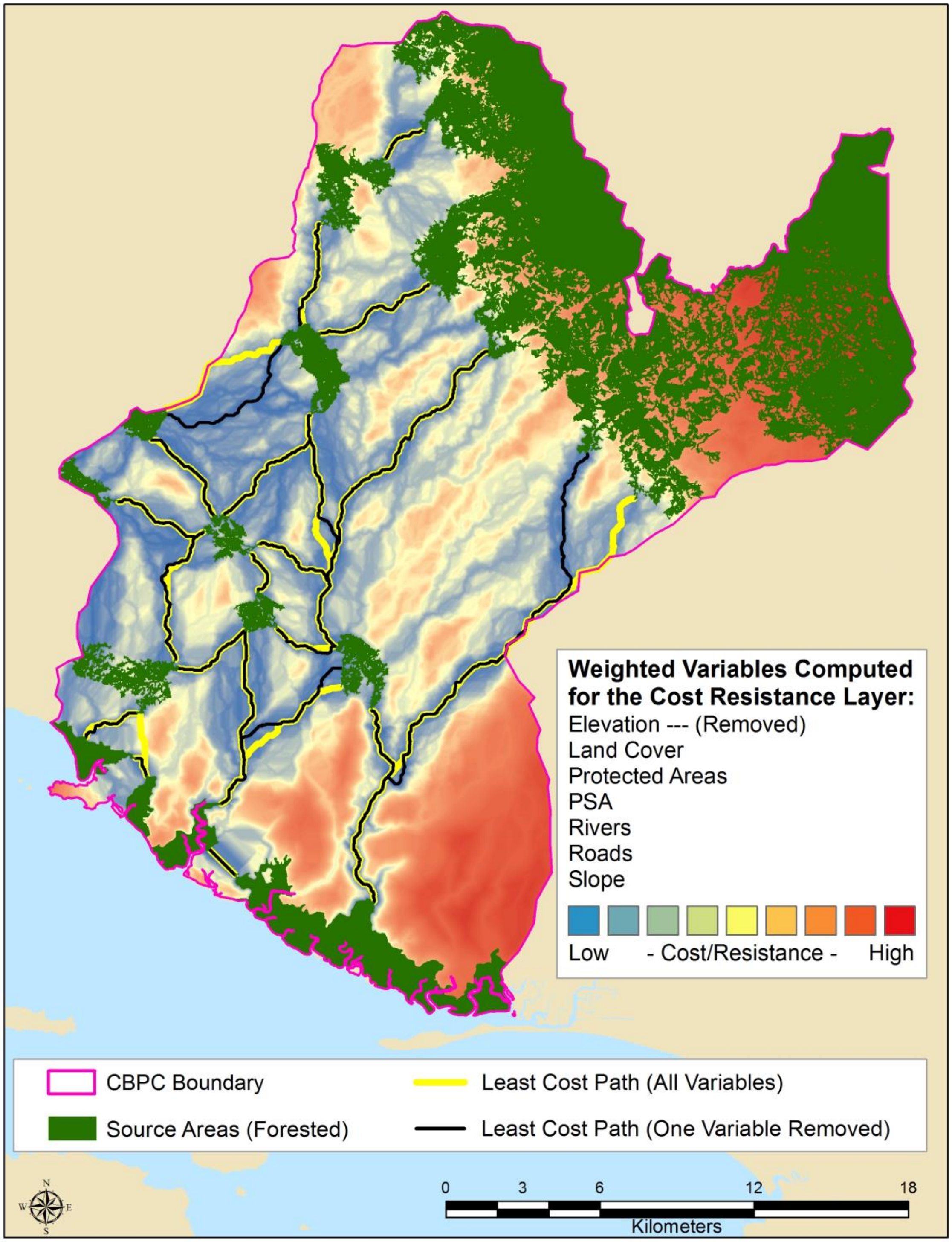

Figure 4.10 Linkage Maker Results with **the Elevation Parameter Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

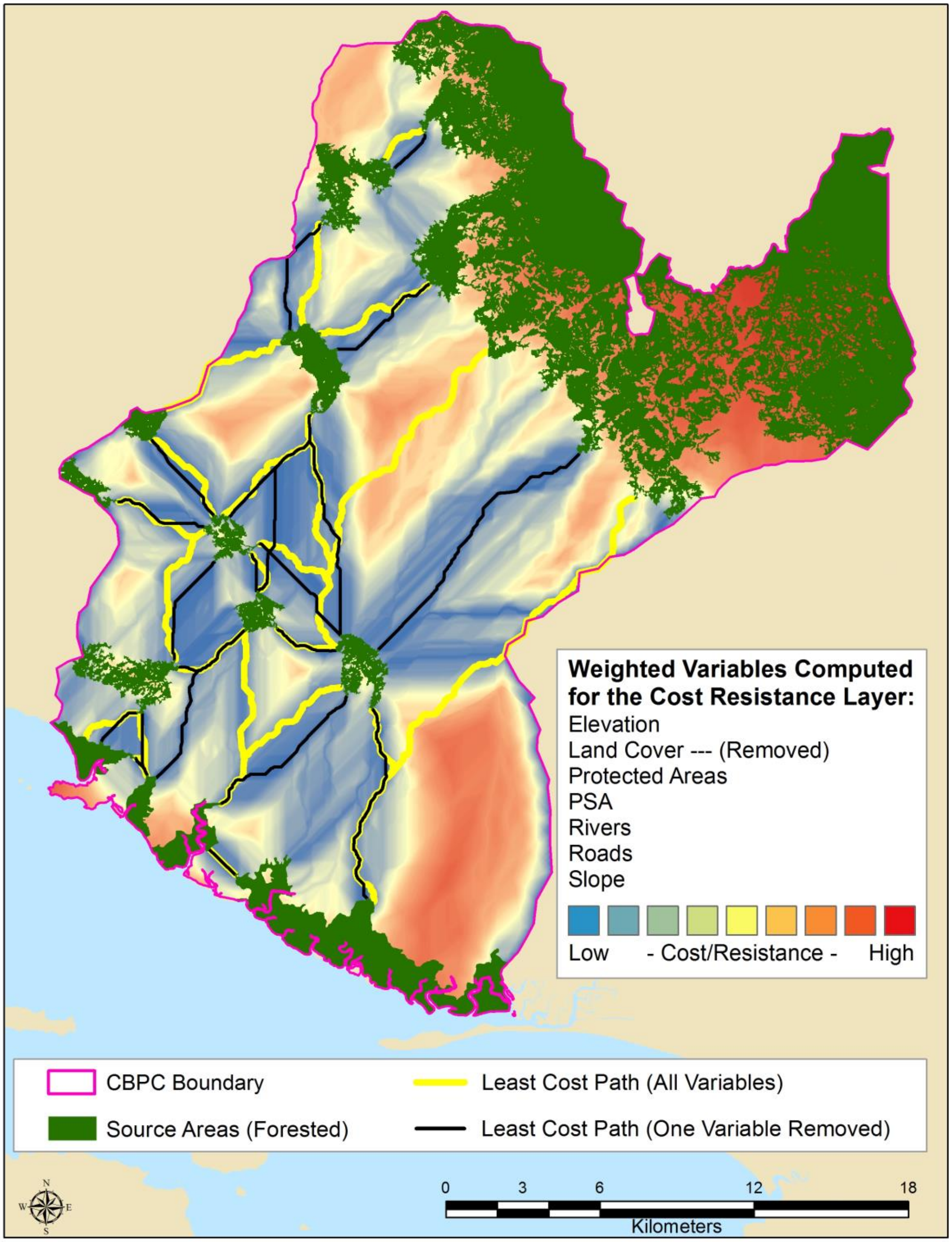

Figure 4.11 Linkage Maker Results with the **Land Cover Classification Parameter Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

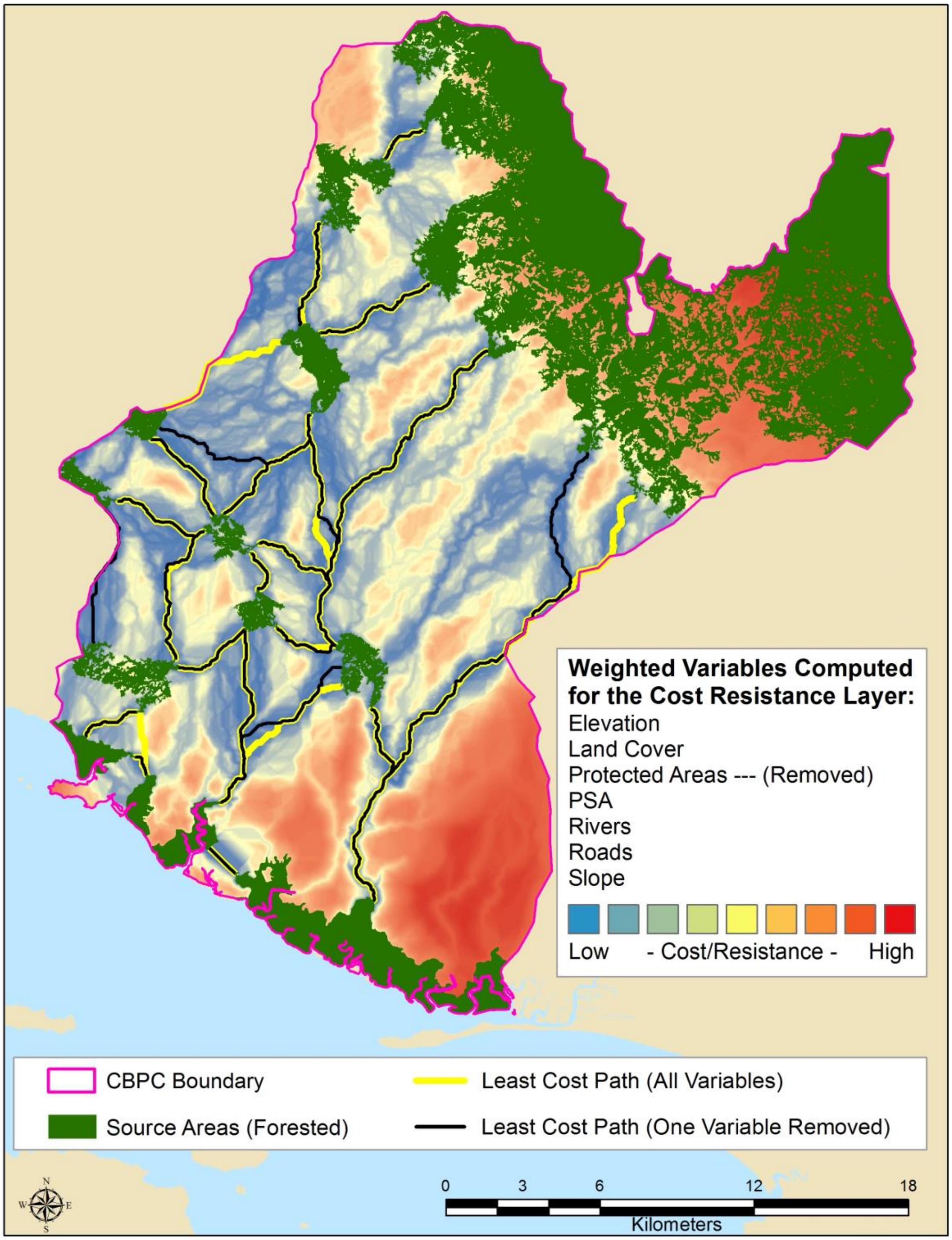

Figure 4.12 Linkage Maker Results with **the Protected Areas Parameter Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

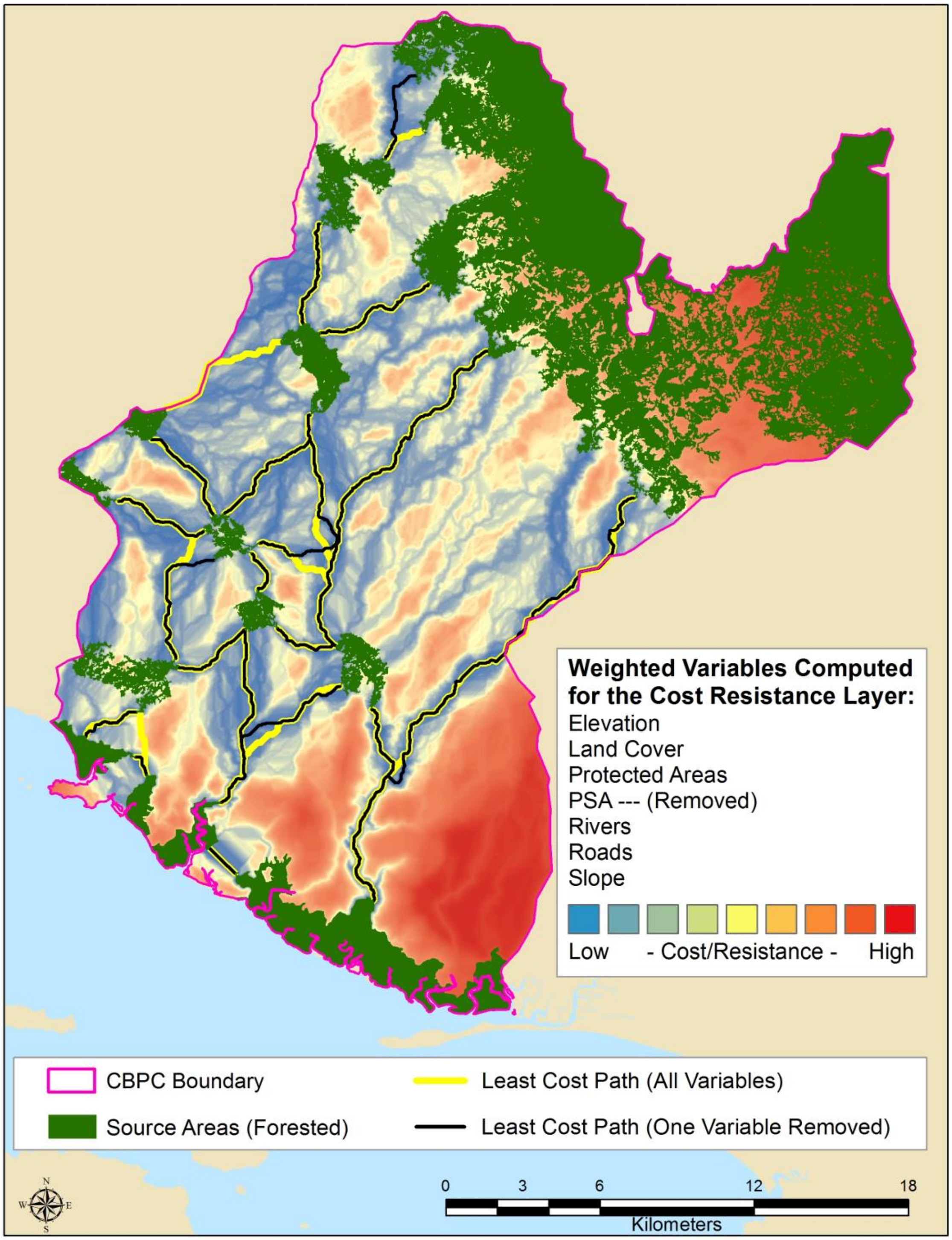

Figure 4.13 Linkage Maker Results with **the Payment for Ecosystem Services Contracts Locations Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

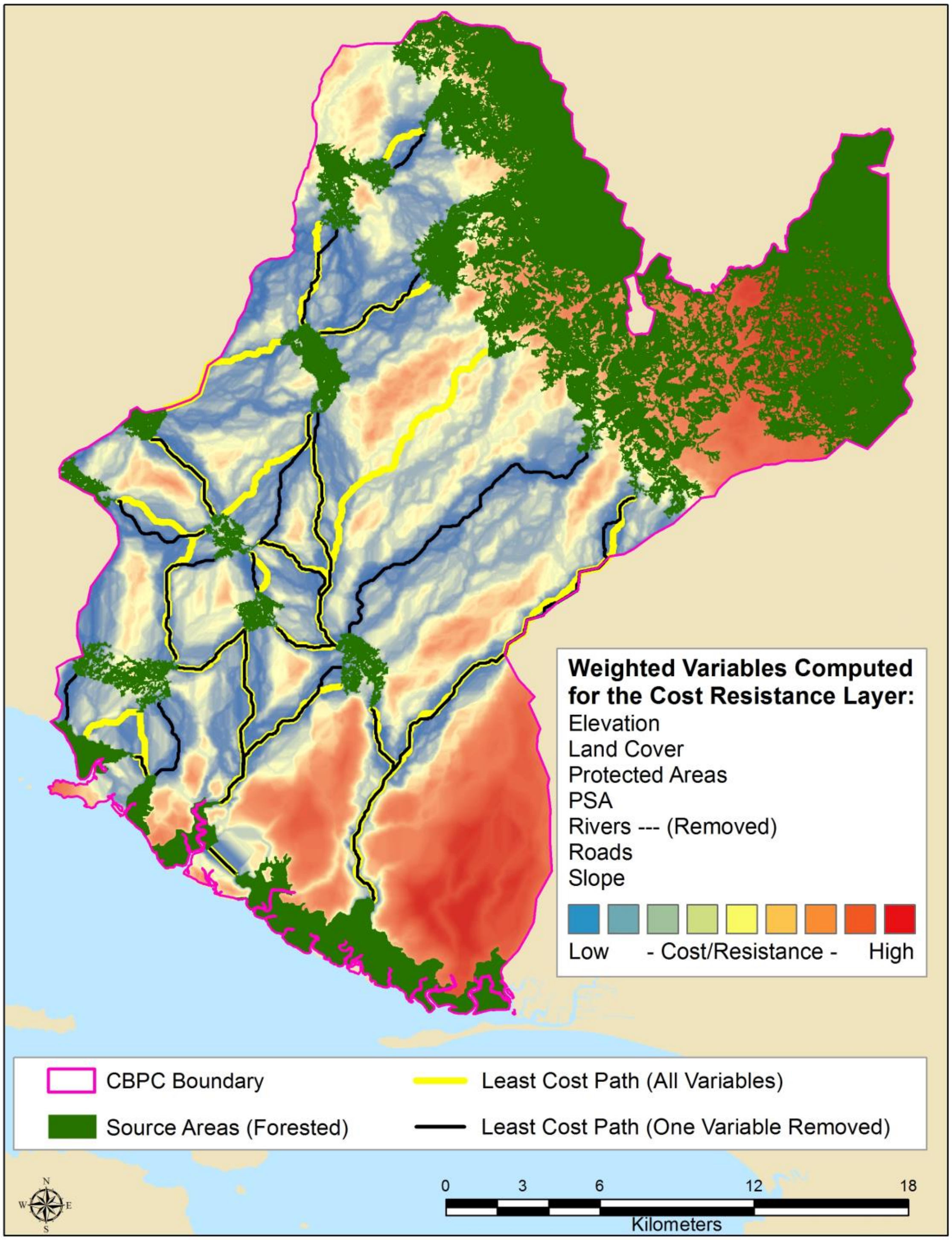

Figure 4.14 Linkage Maker Results with **the River Parameter Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

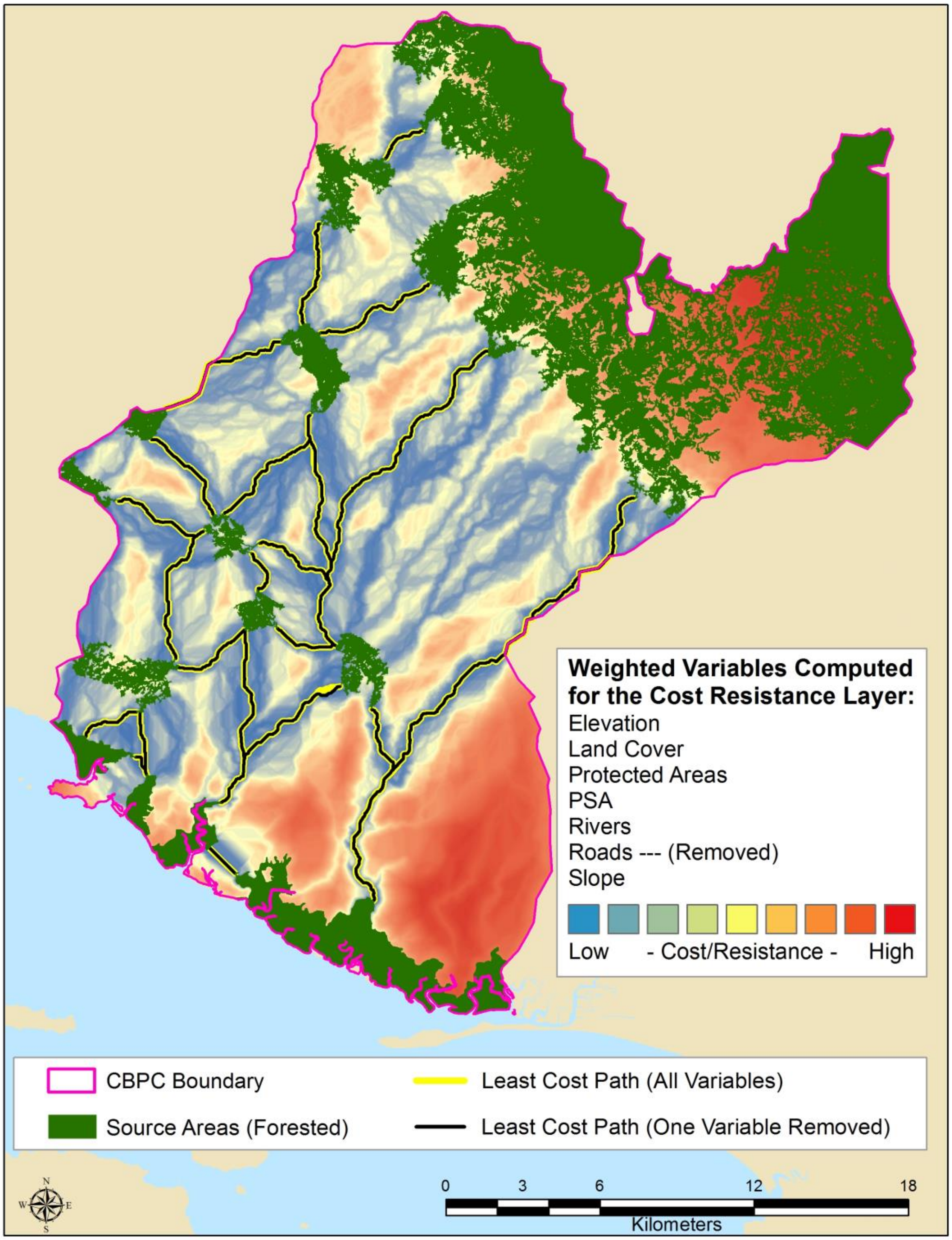

Figure 4.15 Linkage Maker Results with the **Road Parameter Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

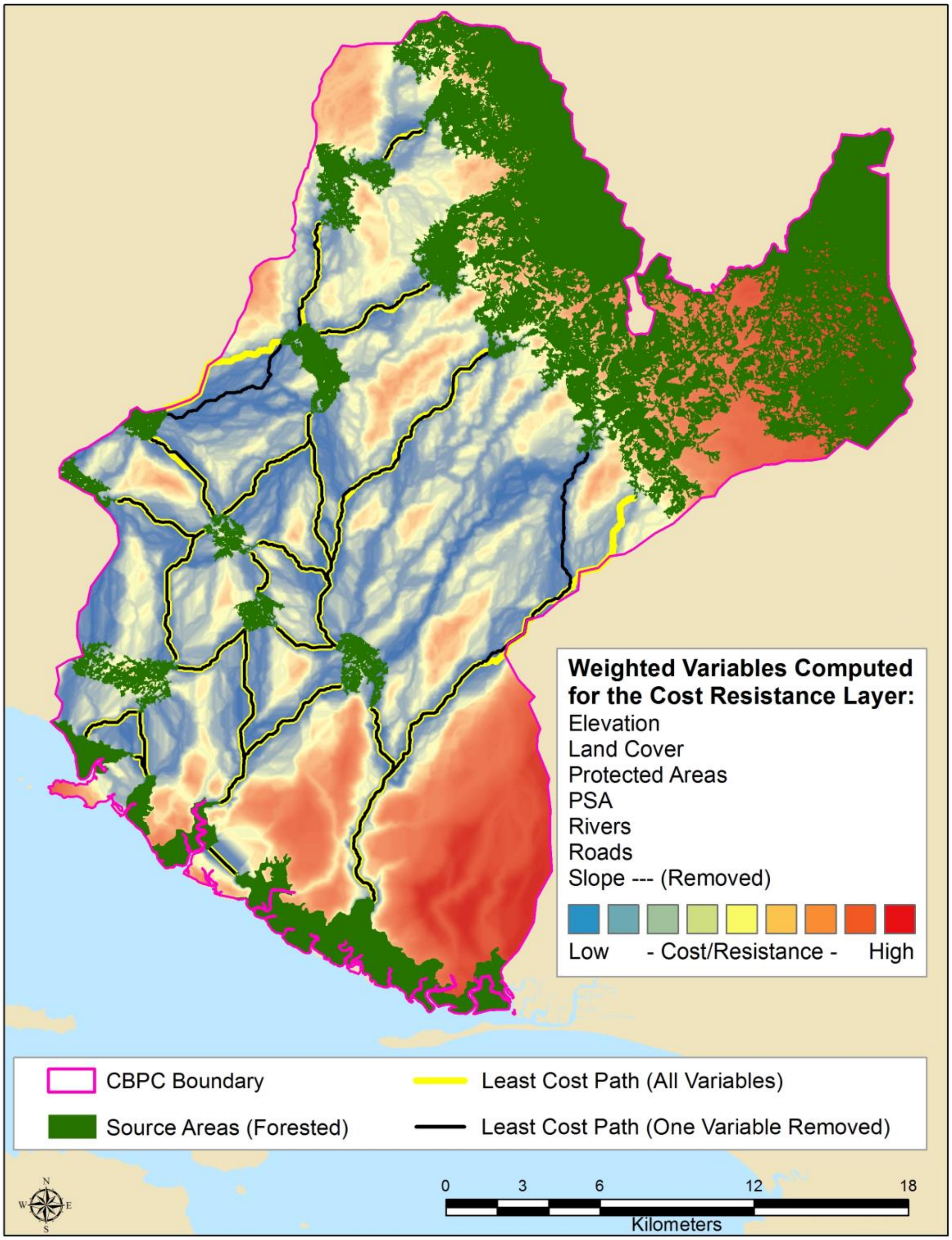

Figure 4.16 Linkage Maker Results with the **Slope Parameter Removed**. The resistance/cost between the forested source areas were calculated along with their least cost paths.

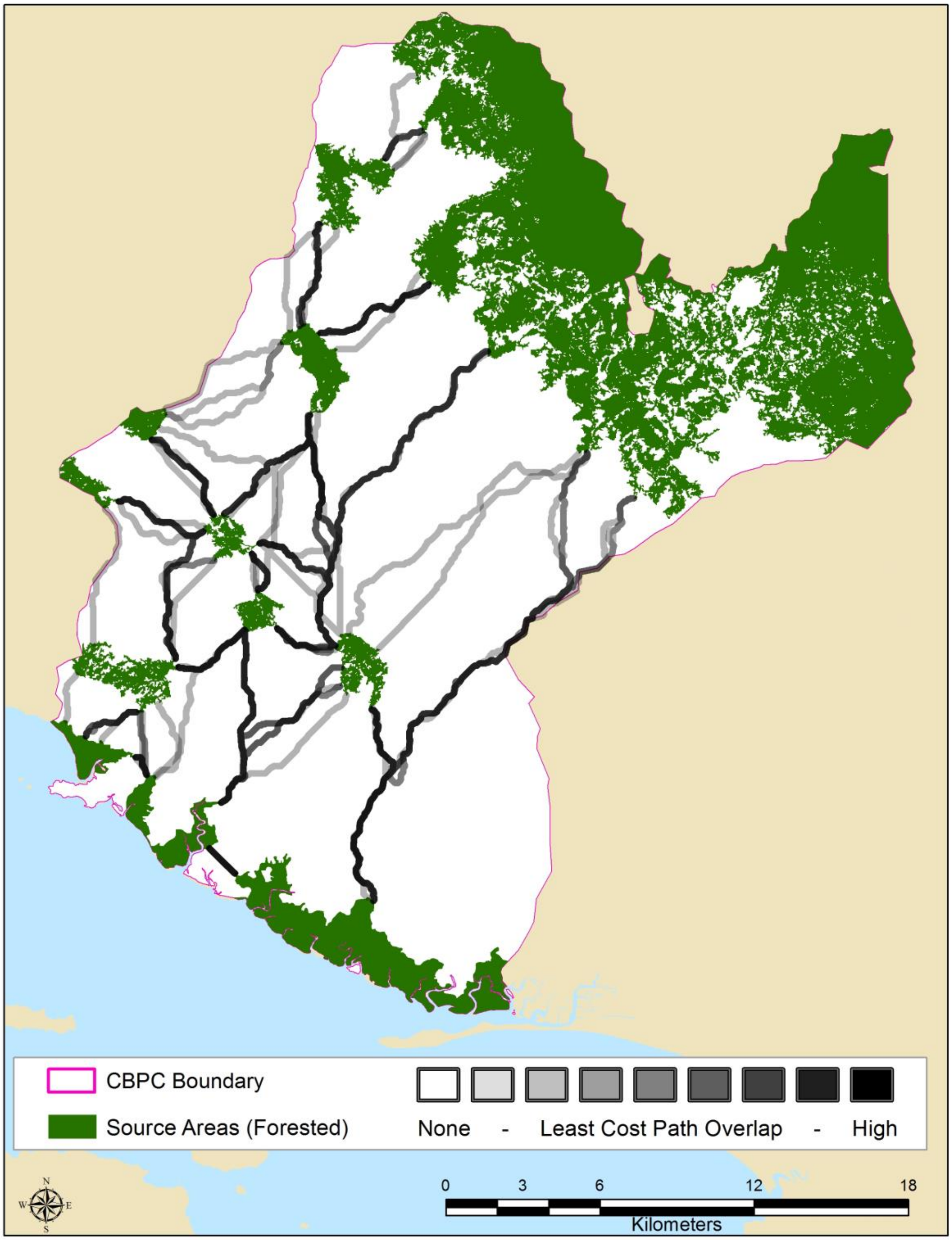

Figure 4.17 Overlapping Least Cost Paths from the Sensitivity Analysis: The darker area represents higher number of overlapping least cost paths.

Discussion

Of the three major watersheds of the Lagarto, Guacimal, and Aranjuez Rivers found within the CBPC, most of the resulting least-cost-paths are found on the Lagarto and Guacimal Watersheds (Figure 4.9b). This was the same result when all parameters were used and when we performed the sensitivity analysis (Figure. 4.17). This may be due to the scarce forest cover that exists between the Monteverde Reserve and the Mangrove forest within the Aranjuez Watershed and most of the industrial agriculture is limited to the southeastern portion of the corridor, which belongs to lower elevations of the Aranjuez Watershed. Additionally, most of the forested areas that served as source polygons connecting the rainforest and mangroves (Figure 4.1) are found in the Lagarto and Guacimal watershed.

The sensitivity analysis helped visualize the effects of each parameter on the model. The influence of Roads on the model was minimal as seen in Figure 4.15. This may be due to the Pan-American Highway transecting the CBPC crosswise and impacting all the watersheds equally. Additionally, limited forest cover in the lower elevations of the CBPC, in turn, limits where least costs paths may be generated. This can be seen in the congruency of the different runs in the sensitivity analysis (Figure 4.17). Land Cover had the greatest difference in the sensitivity analysis (Figure 4.11). According to Beier et al. (2009), improving the reliability of the land cover map can single handedly improve the reliability of any least-cost corridor model when the land cover data has large influence on the results. Updating the land cover layer (based was on 2014 imagery) and using higher resolution imagery (currently 30-meter resolution) would help improve the model.

Through the Linkage Mapper Model, high priority areas for conservation were identified that are predicted to promote forest connectivity within the CBPC. The variables and assignment of resistance values to the least-cost-path model are based on feedback from members of the CBPC Council and include land cover, elevation, slope, rivers, roads, and protected areas. Sensitivity analysis revealed overlaps in designated least-cost-paths that were robust to the decisions about what variables to consider in the resistance layer, potentially indicating areas where protect, restoration, or reforestation efforts could help connect forest patches within the CBPC. Between 2008 and 2013, reforestation program at the UGA-Costa Rica campus planted over 28,000 native trees within the CBPC, predominantly on privately owned farms in close proximity to the campus (Cox et al., 2014) and the program plans to use these results to help them create a more targeted reforestation program.

With the methodology developed in this study, along with the data generated, the CBPC Council will be able to build upon this research, and will be able to modify the parameters of the model to match their conservation priorities along with a more informed and adaptive management strategy. To help account for the varying levels of expertise in using GIS, the data, methodology, and video tutorials needed to replicate this study will be available to the CBPC Council through this website: http://www.stevepadgettvasquez.com

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CHAPTER 5

UTILIZING CIRCUIT THEORY FOR CORRIDOR DESIGN AND EVALUATION OF PAYMENT FOR ECOSYSTEM SERVICES CONTRACTS IN THE BELLBIRD BIOLOGICAL CORRIDOR OF COSTA RICA

Introduction

Declining forest cover, leading to forest fragmentation and habitat loss, contributes to the interrelated and global environmental threats of loss of biodiversity (Turner et al., 2007), and decreased environmental services (Vitousek et al., 1997). This double threat has led to an increased interest in biological corridors, which are defined as connected, linear land areas joining unconnected habitat patches that facilitate animal movement (Beier et al. 2008; Singleton & McRae, 2013). Corridors minimize the effects of habitat fragmentation (Beier & Noss, 1998) and can facilitate species adaptation to climate change (Carroll et al., 2010; Lawler et al., 2010). Additionally, corridors help plant dispersal and retain more native plant species than isolated patches while not promoting the invasion of exotic species, making them a useful tool for biodiversity conservation (Damschen et al., 2006).

Central America's forest was cleared at an alarming rate from the 1950s through the 1980s (Myers & Tucker, 1987), due in part to the expanding cattle industry that converted forests into pasture (Kaimowitz, 1996). In Costa Rica, two thirds of the country's tropical forests were cleared during this period (Guindon, 1996). However, starting in the 1980s, there was an increase in forest cover due to mutiple socioeconomic factors and conservation initiatives (Arroyo-Mora et al., 2005; Calvo-Alvarado et al., 2009). To help promote biodiversity conservation and reforestation, a network of reserves covering about 25% Costa Rica's land mass was created by 2003 (Sánchez-Azofeifa et al., 2003). As of 2017, 44 biological corridors had been established that cover 33% of the country's total land mass (SINAC, 2017). These corridors were designed to improve ecological and climate change resilience while also sustaining local livelihoods. (Townsend and Masters, 2015). Most of the reserves are located in areas that were least accessible for agriculture and thus are found at either very high or very low elevations (Guindon, 1996). The remaining middle elevations in Costa Rica are underrepresented in this network of reserves and forests that are present are fragmented (Sánchez-Azofeifa et al., 2003).

El Corredor Biológico Pájaro Campana of Costa Rica, known in English as the Bellbird Biological Corridor (BBC), encompasses a 664 square kilometer swath extending from the continental divide to the western coast of Costa Rica (Figure 5.1). The namesake of the BBC is the threatened Three-wattled Bellbird (*Procnias tricarunculatus*), one of Central America's largest frugivores with the most complex migratory pattern recorded for a tropical species (Powell & Bjork, 2004). Even though the BBC is a designated conservation area, it is not an intact corridor since it is a mosaic of protected and unprotected areas including large and small-scale agriculture, roads and towns. Maintaining and improving forest connectivity in the BBC is especially important due to forest conversion to agricultural lands and non-forested areas with lower species richness (Daily et al., 2003).

Figure 5.1 - Study Area - The Bellbird Biological Corridor is located in the north western area of Costa Rica and is roughly delineated by the three major watersheds of the Lagarto, Guacimal, and Aranjuez Rivers.

Costa Rica established a program of Payment for Environmental Services (PES) in 1997 as a way to combat deforestation and promote reforestation by providing compensation to people who possess forest lands that provide climate-change-mitigation services, hydro services, scenic services, or biodiversity services (Pagiola et al., 2005; Robalino & Pfaff, 2013). Scenic services fall more in line with cultural ecosystem services which are benefits people obtain from ecosystem that encompasses recreation, spiritual enrichment, cognitive development, and aesthetic experiences (MA, 2005). There is currently no standard methodology to properly evaluate the success of the awarded PES contracts or to determine high priority areas that would maximize returns of PES contracts. As a result, reviews for the program have been mixed.

Countrywide studies claim that PES was not successful in promoting reforestation or reducing deforestation compared to the national rate (Sánchez-Azofeifa et al., 2007; Robalino & Pfaff, 2013). However, site-specific studies claim that PES was successful in reducing deforestation (Arriagada et al., 2012; Fagan et al., 2013). The discrepancies in the studies may be due, in part, to the lack of proper use or limitations of remote sensing and geographic information system (GIS) data in some studies, along with varying methodologies between the studies**.** At the root of the problem, decision makers and stakeholders do not have appropriate access to geospatial data to map and monitor land areas in the program and grant PES contracts efficiently. One common recommendation through different studies is that the PES program would benefit from better targeting of high priority areas to award PES contracts (Sánchez-Azofeifa et al., 2007; Daniels et al., 2010; Arriagada et al., 2012; Robalino & Pfaff, 2013). The ability to identify, monitor, and evaluate PES within Costa Rica is necessary for successful management of the program and spatially explicit connections are necessary for the successful corridor design and management focused on implementing linkages in a landscape through purchasing and/or protecting areas (Krosby et al., 2015).

Landscape connectivity is the degree to which movement of organisms is facilitated or impeded among source patches (Forman & Godron, 1986; Taylor et al., 1993). When connectivity is based on species behavior it is often described as functional connectivity, while connectivity based entirely on landscape structure is called structural connectivity (Kindlmann & Burel, 2008). Despite there being a consensus on the importance of landscape connectivity (Hilty, et al., 2012), there is still much debate about how connectivity along a landscape should be modeled and managed (Beier et al., 2008; Kindlmann & Burel, 2008). Incorporating available legal instruments and tools that already exist are also needed to promote and implement science based connectivity (Lausche et al., 2013).

Connectivity conservation planning has traditionally relied on a focal species approach and on single corridor identification. Building upon the concept of the umbrella species, like a top predator or endangered species, this type of conservation planning emphasizes habitat requirements of the umbrella species and assumes these will include the needs of other species (Lambeck, 1997). The use of multiple focal species is recommended when creating a corridor design since corridors identified for one species are not necessarily used by other species (Beier et al., 2008). At broad scales, focal species connectivity modeling becomes difficult since large numbers of focal species may be required to represent the different habitat types and it would also require months or years, along with substantial financial cost (Beier et al., 2011; Krosby et al., 2015).

Initially, least-cost analysis was the main approach to corridor design (Beier et al., 2008). Least-cost modeling measures the “cost” (for example, energy expenditure) for an organism to move between patches based on information about the landscape, along with behavioral aspects of organisms studied (Adriaensen et al., 2003). A least-cost path, as the name suggests, is the shortest ecological distance between two patches. The least-cost path is calculated from a cost/priority surface, which is the base of the modeling process where areas are assigned cost/priority values that represent varying degrees of structural and functional connectivity (Wade et al., 2015). One of the biggest limitations of the least-cost approach is the underlying assumption that organisms have enough spatial awareness to select a single optimal route (Dickson et al., 2018).

Newer approaches rely on modeling functional connectivity across the landscape as a whole (Kool et al., 2013) and incorporating multiple species (Beier et al., 2008). We focused on circuit theory, which models connectivity across a resistance surface as electric current moving through a circuit, due to its ability to predict multiple pathways that account for the shape and structure of habitat swaths (McRae et al., 2008). Circuit theory takes advantage of analogous properties of a random walk and electricity moving through a circuit (Doyle & Snell 1984). Circuitscape, an open source software that is based on circuit theory of connectivity, has been used to to model animal movement, gene flow, corridor design and landscape connectivity (McRae and Beier, 2007; Dickson et al., 2018).

The goals of the BBC and the PES in Costa Rica are overlapping. The goal of the PES program is to combat deforestation and promote reforestation by providing compensation to land owners who possess forest lands that provide climate-change-mitigation services, hydro services, scenic services, or biodiversity services (Robalino & Pfaff, 2013). The goal of the BBC is to promote forest cover and create a vegetative link between the montane cloud forests and the coastal marshes and mangroves. Identifying areas that increase forest connectivity within the BBC would also identify high value areas for the PES program. We used a method created by Koen et al. (2014) utilizing Circuitscape, to create a map predicting functional connectivity for forest-dwelling wildlife in all directions across the Bellbird Biological Corridor. This approach does not require independent, field-collected data and is not sensitive to the selection of a focal species or the placement of nodes. We then used the circuit connectivity results to evaluate the placement of the awarded PES (2008-2012) contracts in the region.

Materials and Methods

We used Circuitscape software (version 3.5.8, McRae & Shah 2009) that incorporates circuit theory (McRae & Beier 2007; McRae et al. 2008), along with a methodology developed by Koen et al. (2014), to identify areas with a relatively high probability of use within the BBC. We used a land cover data set derived from RapidEye imagery (5-m spatial resolution) developed by GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit, which is the German counterpart to the USAID) with an overall 82.79% accuracy and a kappa value of 0.79 to help measure the amount of forest cover in Costa Rica (SINAC & REDD-CCAD-GIZ, 2015). We generated a cost surface that represented the permeability of the landscape of the BBC and surrounding areas for general forest- and mangrove-dwelling species such as the jaguar (*Panthera onca*) and the Three-wattled Bellbird (*Procnias tricarunculatus*). We focused on these species since the goal of the BBC is to promote forest cover and create a vegetative link between the cloud forest and the marsh. We replicated the three-tier system and criteria values assigned by Koen et al. (2014) in their study to identify areas of high functional connectivity for multiple species of amphibians and reptiles in Algonquin to Adirondack region of eastern North America. For example, we assigned a high cost (1000) to land cover features that we assumed to be unnatural and also relatively impermeable to movement (e.g., primary roads, developed land, intensive agricultural areas and large bodies of water), a medium cost (100) to land cover features that we assumed to be unnatural, but permeable to movement (e.g., secondary and tertiary roads, pastures, forest plantations), and a low cost (10) to land cover features that we assumed would provide natural cover and would represent relatively high permeability to movement (e.g., forest, marshes, riverine and natural vegetation communities). We used the cost surface to create the current density map as one of our inputs in Circuitscape.

By design, Circuitscape produces current density maps with high current at nodes, automatically identifying those areas as highly suitable for animal movement. Koen et al. (2014) developed a methodology that involves placing a buffer around the study area such that the current associated with each node is removed with the buffer, resulting in a current density map that was independent of node placement bias. Koen et al. (2014) also recommend a buffer width that is at least 20% of the study area. To identify an appropriate buffer size for our study, we ran a Buffer Ring Analysis at 1-km intervals up to a 5-km buffer around the BBC.

Circuitscape uses a neighborhood-analysis to assess connectivity between a randomly selected node (or grid cell) and its adjacent cells within a 3 by 3 cell window. Connectivity current or movement from the central cell is allowed either to its four cardinal neighbors (just in the North, South, East, and West direction) or eight cardinal and diagonal neighbors (allowing movement in all directions). At each interval we used a new set of 50 random nodes and connected the eight-neighboring cells as an average cost using the pairwise mode where connectivity is calculated between all pairs of focal nodes. After each iteration, the buffer was removed from the final current density map, leaving just the current density map for the study area of interest (BBC). We then generated Pearson correlation coefficients between all pairs of current density maps. When the correlation of current density maps did not change as the buffer size increased based on a Pearson $r > 0.98$, we determined that the buffer was wide enough to remove the node placement bias.

After determining the appropriate buffer size, we selected eight-neighboring cells as an average cost and used the pairwise mode where connectivity is calculated between all pairs of focal nodes. We used the iteration with 50 nodes that resulted in 1225 unique node pairs as our full pairwise map and our ‘true’ estimate of landscape connectivity to which we could compare to current density maps estimated from fewer node pairs. We then created current density maps using between 2 and 50 nodes. At each iteration, we used a new set of random nodes placed within the buffer region. We also measured the extent diameter of the buffer region containing the randomly generated nodes by running the Minimum Bounding Geometry Tool in in ArcMAP 10.4 (ESRI, Redlands, California, USA; http://www. esri.com/). This was done to compare the geographic footprint (and size) of the buffer region created by each new set of random nodes. After running each iteration, we removed the buffer and analyzed the current density map within the BBC. We then compared Pearson correlation coefficients between the full pairwise current density map (with 50 nodes) and partial current density maps (with nodes 2 through 48) as we increased the number of node pairs. If two current density maps were highly correlated, it meant that the spatial position of relatively high and low current was similar between the two maps. Since this technique produces a current density map that is independent of node placement, there should be little variation in the spatial distribution of the current density as the number of node pairs increases.

The Payment for Ecosystem Services (PES) contract locations were provided by FONAFIFO, the governing body of the Payment for Ecosystem Services Program (Pago por Servicios Ambientales). Between 2008 and 2012, FONAFIFO awarded PES contracts in 56 areas (polygons) within the BBC. In order to evaluate the placement of the PES contracts, we first classified the 50-node generated and full pairwise current density map based on quintiles. This divides the frequency distribution into five equal groups, in ArcMAP 10.4 as recommended by McRae et al. (2013), Although McRae et al. (2013) also suggest excluding areas with highest current and areas with zero current, this was not necessary in our case since; 1) the areas with the highest current were located at the nodes and were removed once the buffer was removed; and 2) there were no areas with zero current within the BBC. We named the quintiles Very Low Current, Low Current, Intermediate Current, High Current, and Very High Current and measured the area of each quintile across all PES polygons. Since the PES polygons account for the entire tract of a landowner, which may include varying land covers and uses, we also identified the highest quintile classification within each PES polygon.

Results

We ran a Buffer Ring Analysis at 1-km intervals up to a 5-km buffer around the BBC to assess the potential effect of node selection and buffer area on circuit connectivity. A summary of the percent area increase for each ring buffer can be found in Table 5.1. A 1-km buffer provided a 21.9% increase of area compared to the area encompassed by the BBC boundary, which is the minimum buffer size that Koen et al. (2014) recommend. When we ran the Pearson's correlation coefficient (r) of all Buffer Ring Analysis cumulative density maps against the 5-km buffer to assess the differences in buffer sizes. We found that all buffers were significantly correlated with $r > 0.95$ at a $P < 0.01$.

Table 5.1 Buffer Ring Analysis Results. 1-km intervals up to 5-km showing the increase in total area, area percentage when compared to the area of the Bellbird Biological Corridor (shown as -km Buffer) and Pearson's correlation coefficient when compared to 1-km buffer.

Km Buffer	Area (sq. km.)	% Area Increase	Pearson's r (vs. 1-km)
0	664	0	N/A
1	813	21.9	1
2	956	43.3	0.95
3	1102	65.2	0.94
4	1252	87.7	0.97
5	1407	110.9	0.95

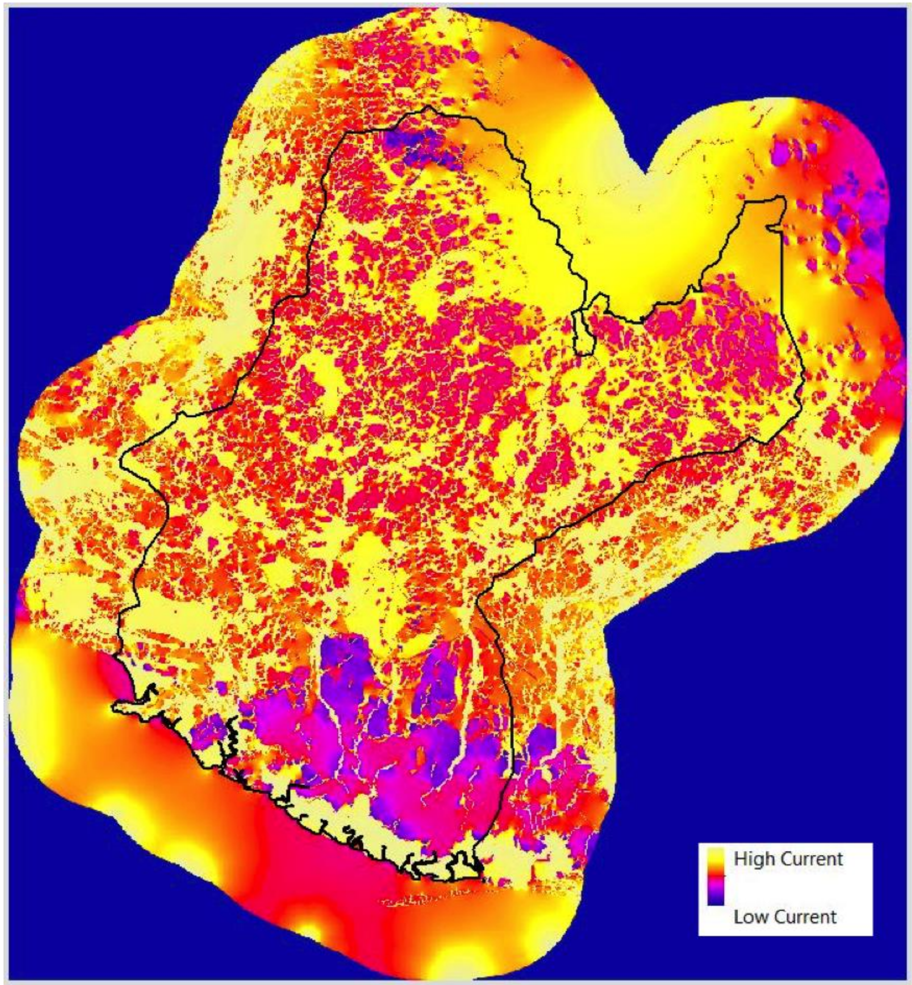

Figure 5.2 Current Density Map: The full pairwise map showing the current for 50 nodes located within a 5-km buffer of the BBC (outline shown in black).

The current density maps started being correlated at 16 nodes (Pearson r = 0.77, P = 0.03) and were highly correlated at 18 nodes (Pearson r = 0.92, P < 0.01) with the full pairwise current density map (generated by the 50 nodes) shown in Figure 5.2. At the 28-node level, the cumulative current density became independent of the number of nodes (i.e., the asymptote) and this level is necessary to characterize connectivity in the interior of the study area (Figure 5.3).

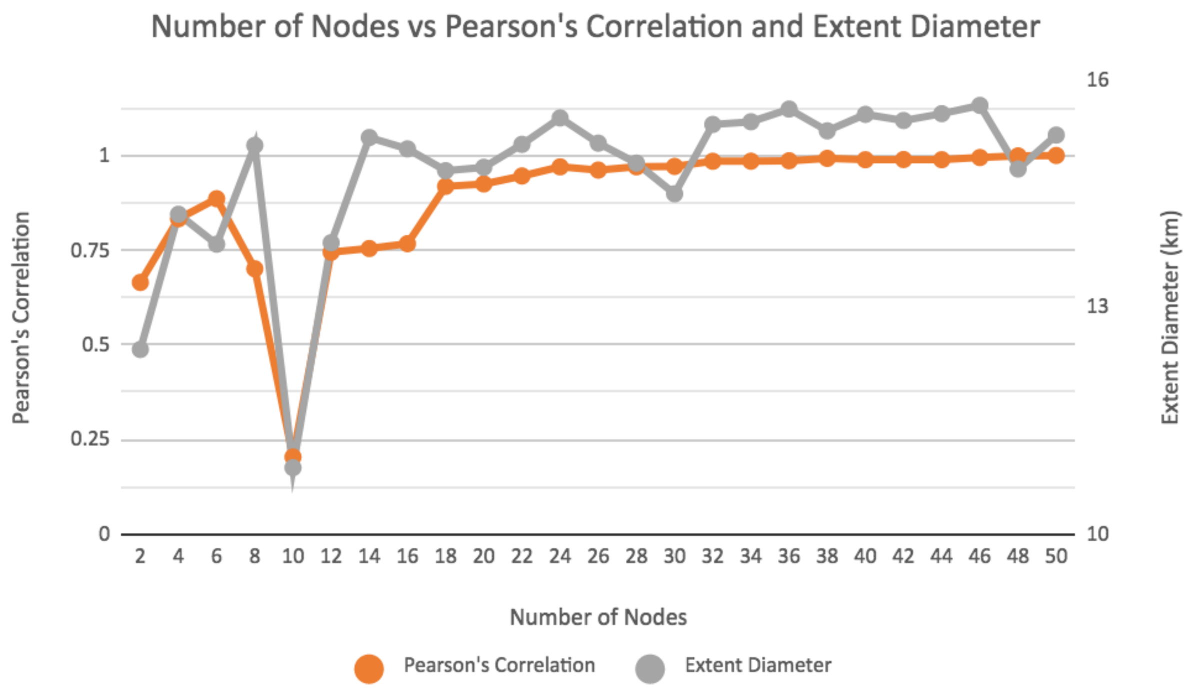

Figure 5.3 Number of Nodes vs Pearson's Correlation and Extent Diameter. Full Pair Wise Map started being correlated at 16 nodes (Pearson r = 0.77, P = 0.03) and highly correlated at 18 nodes (Pearson r = 0.98, P < 0.01). The lowest extent diameter for a correlated node was 30 nodes with a 14.5-km diameter extent.

To evaluate the placement of the PES contracts, we first classified the full pair wise map data into quintiles: Very Low Current, Low Current, Intermediate Current, High Current and Very High Current (Figure 5.4). We then calculated the total area of each quintile across all PES polygons (Figure 5.5). The highest ranking quintile was High Current with 47.9%, followed by Very High Current (20.8%), Intermediate Current (17.6%), Low Current (11.7%), and Very Low Current (2.0%).

When we identified the pixel with the highest current classification within each PES polygon (n=56) (Table 5.2), we found that most of the PES polygons (40/56 or 71.4%) contained pixels classified as Very High Current. The remaining PES polygons had pixels that were

Intermediate Current (6/56 or 10.7%) or High Current (10/56 17.9%). These results show 28.6% (16/56) of the awarded PES polygons did not contain any Very High Current areas.

The areas associated with Very Low Current or Low Currents were pastures, developed areas (towns), and industrialized agriculture. Within the corridor, we found intact forests located in the northern section of the corridor that became more fragmented moving southward towards the gulf. The forested areas in the northern portion were primarily classified into Intermediate or High Current areas. The increase in forest fragmentation explains why there is an increase in Very High Current moving southward in the corridor. In other words, the current becomes concentrated when the flow has fewer options to move randomly from one node to the other.

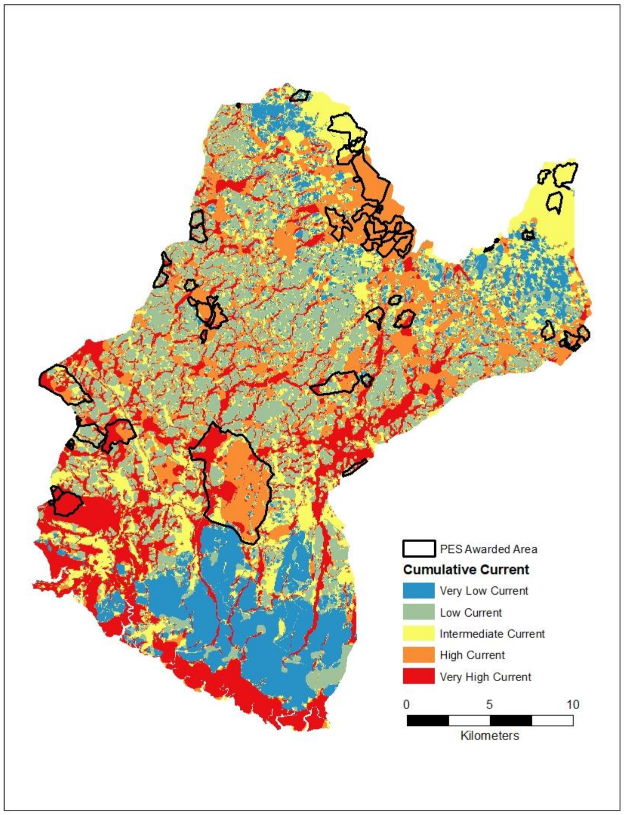

Figure 5.4 PES Awarded Areas (outlined in black): shown on the quintile classification of the full pairwise current density map.

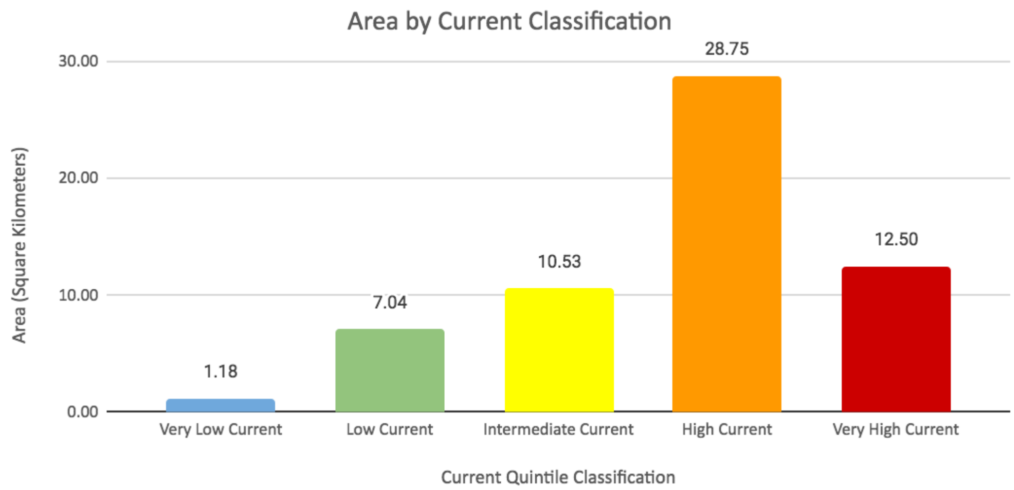

Figure 5.5 Area by Current Classification within all PES Polygons. High Current pixels accounted for nearly half (47.9%) of all the area found within PES Polygons.

Table 5.2 Count of the highest current classification within each individual PES Polygon. Over 70 % (40 / 56) of the awarded PES polygons had areas with a current classification of Very High Current.

Current Classification	Tally of PES Polygons Based on the Highest Current Classification
Very Low Current	0 / 56 (0 %)
Low Current	0 / 56 (0 %)
Intermediate Current	6 / 56 (10.7%)
High Current	10 / 56 (17.9 %)
Very High Current	40 / 56 (71.4%)

Discussion

Since the reported goal of the establishment of the BBC overlaps with the goal of the PES Program, identifying areas that increase forest connectivity within the BBC, would also identify land tracts with high value for the PES Program. We showed how the methodology developed by Koen et al. (2014) can be used to first identify areas that are predicted to have relatively high multispecies functional connectivity as shown by the Very High Current classification within the BBC. We then used these results to evaluate the placement (i.e., functional connectivity) of the conserved areas under PES contracts. Areas with very low current, and therefore very low value for corridor connectivity, were found in developed areas like the city of Santa Elena and areas with industrialized agriculture which are found in the southeast portion of the corridor.

The PES contracts (16/56) that did not contain Very High Current areas were in the headwaters of the streams of the BCC. Mature and intact forests within the BBC were identified primarily as Intermediate and High Current since the northern part of the corridor has minimal fragmentation when compared to the rest of the corridor and current (or movement) can be dispersed in multiple directions. Most of the PES awarded (40/56) within the BCC between 2008 and 2012 contained areas of high functional connectivity flowing in more restricted directions between forest fragments. Future placement of PES awarded areas should focus on areas with Very High Current, in particular in the southern half of the corridor, since in these areas the current has fewer options to move randomly from one node to another and could potentially signal pinch point areas within the corridor. In Costa Rica, studies have shown that riparian buffers facilitate the movement of birds in fragmented forest landscapes (Gillies & St. Clair, 2008) and reduce the impacts of deforestation on benthic macro invertebrates (Lorion & Kennedy, 2009). Overall, the placements of the awarded PES contracts were found to be both beneficial to the increased connectivity of the BBC and true to the PES goal to identify landowners who possess lands that provide hydro services and biodiversity services.

The methodology could be expanded and improved by taking into consideration cultural ecosystem services when developing the cost surface. Cultural ecosystem services are often limited to marketable services such as tourism (Hernández-Morcillo et al., 2013). Incorporating participatory mapping is one way to align biodiversity conservation and cultural heritage preservation in developing sustainable land management strategy (Plieninger et al., 2013).

Underrepresentation of cultural ecosystem services has the potential to bias landscape planning and, thus, threaten the creation of meaningful links between society and nature (Chan et al., 2012).

Within in this methodology, the number of nodes that are necessary to adequately compare connectivity in a given area will vary by shape of the study area. The study area shape can also affect the distribution of the randomly place nodes and the results of comparing Pearson's correlation coefficients between a full pairwise current density and an increasing number of nodes. As shown in Figure 5.3, the 10-node run had a notably lower correlation than any other number of node pairs, including the 2-, 4-, 6-, and 8-node runs. This can be attributed to the small extent diameter created by the 10 randomly generated nodes that happened to be grouped closer together and, thus, define the smallest geographic footprint than any other node pair. Koen et al. (2014) considered that their estimate of connectivity was adequate when the curve of node number graphed against buffer extent diameter (see Figure 5.3) reached an asymptote; in their study it occurred at 15–20 node pairs. In our study, we reached asymptote at 18-22 nodes using a 1-km buffer. Koen et al. (2014) recommends a buffer width that is greater than 20% of the study area. Our ring buffer analysis revealed that our 1-km buffer, which was 21% of the study area, was correlated with the 2-, 3-, 4-, and 5-km buffers (Pearson's $r > 0.95$, $P < 0.01$). In this study we used the cumulative current density map obtained from 50 nodes and resulting in 1225 random node pairs as our full pairwise current density map. However, to replicate or update this study we would recommend using a 1-km buffer and at least 22 node pairs to generate a full pairwise density map.

In terms of connectivity, the approach used in this study differs from other multispecies approaches that parameterize their cost surface. Beier et al. (2009) relied on expert opinion to develop their cost surface for each focal species before overlaying least cost path corridor maps. Cushman and Landguth (2012) used the overlap of connectivity maps of several focal species. Krosby et al. (2015) compared the results of running a species focus model (measuring functional connectivity) with the results of a naturalness-based corridor model (measuring structural connectivity) and found that naturalness-based corridors may offer an efficient proxy for species models, especially in the case of limited or non-existing species movement data. The approach used in this study and following that developed by Koen et al. (2014), parameterized one cost surface that represented the ease of movement for general forest or wetland dwelling species and estimated connectivity between random nodes placed along the perimeter of a 1-km buffer around the BBC. In the cases where there are defined habitat blocks for species-specific studies such as sources, destinations or reserves, then the Beier et al. (2009) approach works well. In the case for the BBC, our approach has the ability to also estimate connectivity in regions that do not have distinct habitat blocks and is not species specific. As field data for habitat and animal movement become more available in the BBC, a hybrid methodology between Beier et al. (2009), Krosby et al. (2015) and Koen et al. (2014) could be developed.

Conclusion

The approach developed by Koen et al. (2014) was ideal for the BBC since the predictive map of multispecies functional connectivity did not require independent, field-collected data which are often not readily available. Additionally, the method was not sensitive to the placement of nodes for connectivity estimation and did not rely on a focal species, such as the Three-Wattled Bellbird. However, field collected data can help validate the results of the methodology as it becomes available. This method is most appropriate in scenarios where there is no reason to place nodes within the study area and thus can estimate connectivity at any point on the surface, rather than between pairs of predefined protected areas, “core” habitat areas, or animal locations. In this case, it can be used to evaluate the placement of previous PES contracts and help guide where future PES contracts should be awarded within in the BCC in order to promote connectivity and additional environmental services.

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CHAPTER 6

CONCLUDING REMARKS

Summary and Conclusion

The findings of this research are of great value to the different stakeholders involved in conservation efforts within the Costa Rican Corredor Biológico Pájaro Campana (CBPC), which includes private reserves, rural communities, research and environmental institutions, private companies, governmental agencies, and educational institutions. This dissertation achieved the goals it set out to accomplished which first tracked forest cover change in the CBPC from 1974 to 2014, then evaluated the geographic distribution of PES contracts awarded between 2008 and 2012, and, finally, identified high priority areas for future conservation efforts that would promote forest connectivity in the CBPC.

In Chapter 2 forest cover change was tracked in the CBPC by analyzing Landsat multispectral imagery, which is freely available through the USGS. We used the Wide Dynamic Range Vegetation Index to classify ten time periods between 1974 through 2014 into five categories: aquaculture, mangrove, forested, industrial agriculture, and non-forested (pasture, bares soils, and urban areas). Overall there was a net gain in forest cover within the CBPC with an estimated 37% of the total area being forested for 2014, up from 30% in 1970. There was also an increase in the amount of industrial agriculture, covering about 12% of the total areas, up from about 9% in 1974. These two categories increased as non-forested areas, mostly pasture, either reverted back to forests or were converted into intense industrial agriculture estimated at about 46% in 2014, down from an estimated 57% in 1974. The amount of mangrove and area used for aquaculture was relatively unchanged since 1979. The middle elevation portion of the CBPC has increased in forest cover, which is helping link the cloud forest to the mangrove, which is crucial in turning the CBPC from a designated conservation area into a functional wildlife corridor.

Even though there was a net gain in forest cover during our time frame, there are areas within the CBPC that have been deforested within the last decade. This study identified areas that have been afforested and deforested between 2011 and 2014 in order to draw the attention of local conservation groups to areas that may be experiencing deforestation pressures. With the results and methodology we developed, along with the freely available Landsat data, local conservation groups will be able to update this study as often as needed, especially considering the dynamic and sporadic process of forest gain and loss within the CBPC. Additionally, updating forest cover maps in the future can help evaluate current conservation and reforestation efforts.

In the mid 1990's, Costa Rica established its Payment for Environmental Services (PES), known in Spanish as Pago por Servicios Ambientales. Determining the effectiveness of thePES program has proven difficult since forest cover, especially since a study within the CBPC examining parcel-level impacts of changes in landscape shows that forest cover is an insufficient proxy for conservation success (Allen & Padgett Vásquez, 2017). Previous studies in Costa Rica claim that improving the spatial targeting, in other words, the intentional geographic distribution, ofPES contracts would improve the effectiveness of thePES contracts (Robalino & Pfaff, 2013; Wünscher et al., 2008). In Chapter 3 we evaluated the spatial targeting of thePES contracts awarded between 2008 and 2012 and found that the overall the spatial targeting of thePES contracts within the CBPC was positive in promoting forest connectivity and providing environmental services. Our Nearest Neighbor analysis results demonstrated that each individual year, thePES contracts were not clustered within a particular region within the corridor. In terms of representation of the Holdridge Life Zones, thePES contracts include almost all the Holdridge Life Zones found within the CBPC (9 out of 11 Zones). The majority of thePES contracts (76%) were located within 30-m of a stream, which helps promote hydro-services and biodiversity services. Targeting futurePES contracts in areas designated as high priority within the corridor would have greater impacts.

In Chapter 4, we used stakeholder-identified factors to determine areas important for landscape connectivity, thereby identifying potential areas for conservation and reforestation that would help promote forest connectivity. We used Linkage Mapper to generate resistance layers and calculate least cost paths between forest areas exceeding 1.5 km^2. With the results and methodology we developed, local conservation groups within the CBPC will be able to update the results based on new data or conservation focus. Additionally, results identified high priority areas for futurePES contract. There are three main watersheds within the CBPC: Lagarto, Guacimal, and Aranjuez. Most of the resulting least-cost-paths are found on the Lagarto and Guacimal Watersheds. The Aranjuez Watershed has scarce forest cover that exists between the Monteverde Reserve and the mangroves in the gulf of Nicoya. Additionally, most of the industrial agriculture is limited to the southeastern portion of the corridor, which belongs to lower elevations of the Aranjuez Watershed.

One overarching goal of this study was to help create a baseline of geospatial data to help inform conservation efforts in the CBPC. In order to maximize the impact of this study, we will also share the data collected and methodology developed in order to allow local stakeholders to update and customize the processes so they can make data driven decisions. This goal falls in line with Strategic Communication requirement of ICON.

In Chapter 5, we used a novel technique using circuit theory to identify priority areas for conservation and to evaluate the placement ofPES contracts. We used a method created by Koen et al. (2014) utilizing Circuitscape, to create a map predicting functional connectivity for forest-dwelling wildlife in all directions across the CBPC. This approach does not require independent, field-collected data and is not sensitive to the selection of a focal species or the placement of nodes. We then used the circuit connectivity results to evaluate the placement of the awarded PES (2008-2012) contracts in the region. Additionally, the Circuitscape results can be used to help prioritize futurePES contracts within the CBPC.

ICON and Strategic Communication

I've heard multiple times at orientation and seminars that ICON is called "Integrative" and not "Integrated" because the process of integrating different lenses and disciplines is never really complete. As you continue your research and gain new knowledge you are continuously updating your approach. One interpretation of this nomenclature is that Integrative Conservation is a dynamic process. Coming from an applied approach to research, I wanted to make sure that my research was also dynamic and that its effects did no culminate in just a publication. This is one reason why ICON students are expected to have a strategic communication component to their research. Seeing first-hand the limited availability of data, I wanted to find a way to increase access to data.

Even though the data and plug-in for Linkage Mapper are freely available, the research methodology could be improved if the study was carried out utilizing a geospatial software that is freely available such as QGIS (QGIS Development Team, http://www.qgis.org/en/site/) or Google Earth Engine (Google Inc., Carnegie Mellon University, NASA, USGS and TIME; https://earthengine.google.com/). These online GIS and image processing platforms are free to users with internet connections and their use is becoming more widespread. Over time the program functionality is being improved and more robust, which can help overcome financial barriers encountered by some natural resource and conservation groups who cannot afford proprietary software licenses. The geospatial data, along with the video tutorials on how to replicate these studies, are available at http://www.stevepadgettvasquez.com facilitating local stakeholder within the CBPC to update or customize this study and to help with any learning curve associated with the use of this methodology. I also provide on my website, links to free online tutorials on how to use remote sensing for conservation management.

The exposure and networking that resulted from joining ICON are some of the biggest benefits of the program. I've had the chance to meet researchers from different disciplines and we have had the chance to share ideas and even tackle some research questions. This can be best exemplified in the manuscript that Karen Allen, a fellow ICON graduate student in Anthropology, and I published 2017. We combined research techniques from both our disciplines in the form of remote sensing analysis paired with interviews and ethnography in order to unravel the relationship between national policy, forest regrowth, and social-ecological sustainability. Had I not been part of ICON, this research may not have occurred. Additionally, part of the methodology of this dissertation, in particular the corridor modeling from Chapter 4, was used for a NASA ROSES multi-year grant proposal submitted by Dr. Roberta Salmi. Lastly, part of the same methodology is currently being considered for a reforestation and carbon credit program in the Guanacaste region of Costa Rica by Dr. Quint Newcomer. As a geospatial analyst who has been focused on applied remote sensing and GIS, I now know what it means to work in research that is both integrative and collaborative across multiple disciplines.

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