LONGITUDINAL ANALYSIS OF THE ROAD NETWORK DEVELOPMENT AND LAND-COVER DYNAMICS IN LOP BURI PROVINCE, THAILAND, 1989-2006

By

RISA PATARASUK

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To my family, and friends
In memory of Dr. Kwadwo Konadu-Agyemung

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Risa Patarasuk

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This dissertation investigates the relationships between road network development and land cover in Lop Buri Province Thailand between 1989-2006. The dissertation is divided into three major chapters (2-4), each of which is a stand-alone journal paper. Chapter 2 examines the relationship between distance to roads and land-cover trajectories. First land-cover classes were determined; then the distance from roads was mapped against the land-cover. The results show that most of land-cover change occurs within 6 km of roads, whether existing or newly built.

Chapter 3 examines other drivers of land-cover change by using logistic regression analysis. The focus was on two major particular trajectories: changes to upland crops and loss of forest. The results showed the most influenced for these two types of land-cover trajectories are slopes, distance to forest edge, and distance to towns.

Lastly, in Chapter 4, network analyst was use in determining how connectivity can relate to land cover and land-cover change. Fifty-six intensive study areas (ISAs) were selected in this analysis. Then I compared the differences between each type of land

cover in the areas that have gone through road network development and the areas that have not gone through road network development. The results revealed that areas that have road network development have significant changes in the amount of forests, upland crops, and plantation landscape.

This dissertation concludes that roads are the main contributor of land-cover change in Lop Buri province. Thus, human activities of road building can drive the environmental changes of land-cover change. This study has enhanced the knowledge of human-environmental interaction and transportation geography through incorporating an array of theories, methods, and tools such as GIS, remote sensing, and spatial statistics.

CHAPTER 1
INTRODUCTION

“Roads promote economic development, but they also facilitate deforestation” (Chomitz & Gray, 1996). This quote implies that even though roads bring benefits in terms of social and economic development, they can also affect the natural systems through which they pass via changes in land-cover such as the removal of forests. The primary purpose of this dissertation is to investigate the nature of the relationships, between road network development and the dynamics of land cover in Lop Buri Province, Thailand.

The Role of Roads and Road Network Development

Roads serve as conduits linking places, regions, and economy together, facilitating the movement of people, goods and services. They also play a central role in economic development and enhancing social transactions (Forman, et al., 2003; Rodrigue, Comtois, & Slack, 2009). Road network development is usually a result of a nation’s public policy serving several purposes such as facilitating military movement and national security (e.g. Interstate Highway System in the U.S.A.), enhancement of relationships between neighboring countries (e.g. Thai-Laos Friendship Road/Bridge), and promotion of local and regional social and economic growth (Australian Agency for International Development (AusAID), 2009; Caldwell, 1974; Muscat, 1990).

In many countries, particularly in the developing world, road development in recent decades has been intended to support social and economic development in attempt to alleviate extreme poverty, particularly in rural areas (Puri, 2006). Roads further promote social and economic development by providing the basic infrastructure for subsequent investment and linkage between urban (e.g. major population centers, employment centers, and market areas) and rural agricultural areas. Furthermore, road development in rural areas furnishes not only mobility, but also greater accessibility to major markets for their agricultural products, reducing both transport costs and time. Improved access to market areas in turn benefits farmers through increased household income by means of increased sales of export crops (Buurman & Rietveld, 1999; Deichmann, Kaiser, Lall, & Shalizi, 2005; Gutierrez & Urbano, 1996; Lampe, 1983; Nagurney, 2005). In addition to the economic benefits that roads bring, other social benefits associated with road network improvements include better access to education (Bourdet, 1998), better health care delivery (Airey, 1992), and employment opportunities (Windle & Cramb, 1997).

Despite many benefits that roads bring, they also pose negative socio-economic and ecological consequences. For examples, roads induce higher traffic into the area; thus, creating noise nuisance for local residents (Phan, et al., 2010). Higher traffic generates higher air pollution levels through vehicle combustions and in turn leads to residents' health problems such as cardiovascular diseases (Beelen, et al., 2009). Other effects that roads can bring include runoff that affect aquatic environments (Starzec, Lind, Lanngren, Lindgren, & Svenson, 2005); wildlife-mortality through road kills (Smith, 2003); and landscape fragmentation and land-cover change through human access (Arima, Walker, Perz, & Caldas, 2005). The essence of this dissertation is to focus on ecological effects of roads through land-cover change.

Land-Cover Change and Road Network Development

Land use and land cover change (LUCC), mainly as a consequence of human activities, is a major contributor to global environmental change. Land-cover change is dominated by human activities with complex spatio-temporal dynamics, and is a result of complex interactions between human actions and the physical environment. LUCC often leads to complex landscape mosaics and mixtures of land-cover types (Hu & Lo, 2007; Mertens & Lambin, 2000). Conversions of one land-cover type to another can affect climate systems (Dale, 1997; Taylor, Lambin, Stephenne, Harding, & Essery, 2002), hydrological systems (Bruijnzeel, 2004; Mendoza, Bocco, López-Granados, & Bravo Espinoza, 2010; Twine, Kucharik, & Foley, 2004), and natural habitats (Homewood, et al., 2001; Serneels & Lambin, 2001a). Many studies in land-cover change emphasize the loss of forest cover, as its removal can have negative environmental consequences, such as loss of carbon storage and habitat (Brooks, et al., 2002), and the alteration of local and regional climates (Dale, 1997).

Although road network development, which results largely from human activities, plays a role in social and economic enhancement, roads have been shown to lead to land-cover change (Burgi, Anna, & Nina, 2005; Geist & Lambin, 2002; Lugo & Gucinski, 2000). The development of roads is a primary mechanism of land-cover change by allowing increased access to destinations including land and towns (Saunders, Mislivets, Chen, & Cleland, 2002; Stone, Brown, & Woodwell, 1991). Road development that allows human access to land, particularly to forested areas, has been studied at large in tropical rainforests in the Amazon region (Alves, Pereira, Sousa, Soares, & Yamaguchi, 1999). However, better accessibility to markets resulting from road network development can encourage people to convert land, particularly, from forests to agricultural landscapes as evidenced in many agrarian settings. Development of roads though network extension or road improvements (e.g. from unpaved to paved) allows farmers to reduce their travel time and transportation costs to market areas (Dorosh, Wang, You, & Schmidt, 2009; Verburg, Overmars, & Witte, 2004). Improvement of road conditions from unpaved to paved also permits vehicles to gain better access to farmlands and markets during wet seasons (Verburg, et al., 2004). Farmers increase agricultural profitability by expanding crop production along the developed roads (Dorosh, et al., 2009; Hafner, 1970; Soares-Filho, et al., 2004). Similarly, a developed road network in a large metropolitan setting induces people to settle farther from central business district. These in turn have led to suburban development at the expense of agricultural and natural landscapes (Lo & Yang, 2002; Nathalang, 1986; Stanilov, 2003; Torrens, 2006).

Impacts of roads on a region's ecology are of concern in tropical regions, mainly developing countries, where the road infrastructure is expanding rapidly into areas of high biodiversity such as forests. These developing countries such as Thailand are also coping with their own economic and the social changes. Therefore, roads pose particularly challenging problems to those interested in land conservation because the development of a road network is strongly positively correlated with economic and national wealth while simultaneously being linked to the scale of ecological disturbance and natural resource degradation (Wilkie, Shaw, Rotberg, Morelli, & Auzel, 2000). Thus, it is important to understand roads and land-cover interactions in terms of the influence of roads on the landscape.

Road Network Development in Lop Buri Province

The road network of Thailand has been developed to serve several purposes including supporting military movement, enhancing relationships between neighboring countries (e.g. Thai-Laos Friendship), and social and economic development. Since the inception of the First National Economic and Social Development Plan in 1961, and other subsequent National Plans, road development in Thailand has accelerated greatly. The purpose of road network development stated in the National Plans is to improve the quality of life through poverty alleviation, to enhance economic development, and to increase linkage among the regions (Hughes, 1971; Lop Buri Provincial Office, 2006; Puri, 2006). One of the National Plan’s strategies is to facilitate the transport of commercial crops from remote areas to market areas in major cities and for subsequent distribution to foreign markets (Rojnkureesatien, 2006), as well as coping with the rapid economic agricultural sector growth experienced during the 1980s to early 1990s (Dixon, 1999; Ekasingh, Sungkapitux, Kitchaicharoen, & Suebpongsang, 2007; Intarakumnerd, Chairatana, & Tangchitpiboon, 2002; Yokakul & Zawdie, 2009). However, when in 1997 the Asian Economic Crisis hit Thailand, investment in public infrastructure including the road network was delayed (Ministry of Construction, 1999). The economy recovered by 2003 but investment in the transportation sector has never returned to the pre-crisis position (Economic and Social Commission for Asia and the Pacific (ESCAP), 2005, 2009)

In Lop Buri province, road network development was initiated by General Por Piboonsongkram during the 1930s to support military activities and turned Lop Buri into a military-based province. Piboonsongkram’s policy transformed Lop Buri City into the hub of economic development in the upper central region of Thailand (Office of Information and Technology: Thepsatri Rajabhat University, 2008). In recent decades, roads have been built and improved to enhance social and economic activities in conjunction with the various National Plans.

Major highways passing through Lop Buri province include National Highway No. 1 (Figure 2-1), which is one of the four most important highways in Thailand (Department of Highways District 1 Lop Buri, 2008; Lop Buri Provincial Office, 2006). This highway plays a significant role in land transportation connecting Bangkok with Lop Buri City, and the Northern regions of Thailand. Other highways include Highway 21 and Highway 205 which link places within the province and the Central and Northeast Regions. In 2006, Lop Buri reported a total road length of 4,723 km (Department of Environmental Quality Promotion, 2007; Department of Highways, 2007b). However, this is not evenly distributed throughout the province. In the western and the eastern sections, the road network is denser than in the central section (Figure 2-3). The road network in the southeastern section has been altered due to the construction of Pa Sak Dam/Reservoir, started in 1994 and was completed in 1999.

Study Area

Lop Buri province is located in the Central Region of Thailand (Figure 2-1). The province consists of 11 districts (called “amphoe” in Thailand). The province is approximately 150 kilometers from the capital, Bangkok, and acts a gateway from Central Thailand to the Northern and Northeastern regions. It is one of the wealthier provinces in Thailand (Felkner & Townsend, 2004), being ranked 19th out of 76 provinces in GDP per capita (Lop Buri Provincial Office, 2010). The province’s population in 2008 was 753,470 (Lop Buri Provincial Office, 2010), the majority of which is engaged in the agricultural sector. Amphoe Muang Lop Buri (Lop Buri City) is the most populated district with a population of 249,620 persons, followed by Amphoe Chai Badan (Chai Badan City) with 90,182 persons. These two districts are the most important centers of economic activity in the province (Lop Buri Provincial Office, 2010; Oung-youang, 2000; Thailand National Statistical Office, 2006).

At approximately 6,600 sq.km, the province is at about the median of provincial land areas and is located between 14º39′ and 15º35′N and between 100º24′ and 101º26′E between the Chao Phraya and the Pa Sak River. Elevations range from 5-840 meters above sea level, although approximately 55% of the land area has an elevation below 100 meters (Figure 2-2). These low-lying areas are found primarily in the west and scattered among the northeast. Areas between 100-300 meters comprise approximately 30% of the province and are scattered in the northern, central, and eastern regions; while those areas above 300 meters are scattered in the central and eastern regions.

Lop Buri has a monsoon climate. During May to October the southeast monsoon from the Indian Ocean, brings rain which is bimodal in its temporal distribution. The highest amount of rainfall is in September and the second highest is in May. During the 30 year period, 1961 to 1990, average May rainfall was 170 mm and 280 mm in September. Occasionally the intense monsoon causes flooding in the province and reduces road quality and access. Between November and April, the dry season, the northeast monsoon brings dry air from China. The average daily minimum temperature from 1961-1990 was 23.3ºC and the maximum was 33.3ºC.

April is usually the hottest month and December/January are the coldest months (Lop Buri Provincial Office, 2006; Thai Meteorological Department, 2008; Worakawin, 2003).

Dissertation Research

The main purpose of this study is to investigate the nature of relationships between road network development and land-cover dynamics in Lop Buri province from 1989 to 2006. As mentioned earlier, road network development in Thailand during the past several decades has been developed to enhance social and economic development; however, they can contribute some ecological impacts such as landscape change in Lop Buri province as evidenced elsewhere in the world. As roads are developed, the network configurations also change and can influence the extent in which people have access to their destinations. This, in turn, can affect landscape in the extent or beyond the extent where roads were developed (Forman, et al., 2003). Thus, it is important to investigate and understand how roads interact with landscapes.

This dissertation has put a step forward to study various aspects of road network development including distance and connectivity. Furthermore, the study also assesses other drivers that might have influence land-cover in Lop Buri province. Roads might not be the sole driver of land-cover change as land-cover change can results in a combination of multi-factors (Geist & Lambin, 2002). The main questions investigated in this research are:

1. How does land-cover vary across the different spatial patterns of road network?

2. How do distance to roads and road connectivity affect land cover and land-cover trajectories in Lop Buri from 1989-2006?

3. What are major drivers that contribute to land-cover change?

4. Are there any differences in the amount of land cover in areas that have gone through road network development versus areas that did not have road developed?

This study uses various methods and tools to seek answers to these research questions. Methods and tools employed include network analysis in ArcGIS, land-cover classification processes in ERDAS Imagine, graph theory-based network indices, and logistic regressions in SPSS. Finally, the dissertation contributes to a greater context of human-environmental interactions agenda.

Dissertation Outline

The dissertation comprises three related research articles to be submitted for publication in refereed journals (Chapters 2 to 4). As of this writing, Chapter 2 has been accepted for publication in *Applied Geography*, Chapter 3 will be submitted for publication in *Singapore Journal of Tropical Geography*, and Chapter 4 will be submitted for publication in *Journal of Transportation Geography*. Chapter 2 investigates how the road network of Lop Buri province has driven changes in land cover. It classifies land-cover into six classes (forest, water, plantation, rice, upland crops, and built-up) and analyzes the amount of land-cover change from 1989-1998, 1998-2006, and 1989-2006. Finally, the study combines changes in road network and land-cover dynamics to examine the land-cover change as a function of distance to the nearest roads.

Chapter 3 explores biophysical and social factors that contribute to land-cover change in the province. The study employs logistic regression to explain factors that cause land-cover change. Two particular land-cover changes are analyzed: 1) from forest to non-forest, and 2) and any land-cover classes that are converted to upland crops.

Chapter 4 employs graph theory to examine the connectivity of the road network and how such connectivity might affect land cover. The study compares areas that have and have not experienced road development. Fifty-six intensive study areas (ISA) were chosen to further investigate this relationship. Lastly, Chapter 5 provides an overview of the conclusion of each paper and a statement of the contribution of the study.

CHAPTER 2
LONGITUDINAL ANALYSIS OF THE ROAD NETWORK DEVELOPMENT AND LAND-COVER CHANGE IN LOP BURI PROVINCE, THAILAND, 1989-2006

Land use and land cover change (LUCC), mainly a consequence of human activities, is a major contributor to global environmental change. LUCC is driven by combinations of social, biophysical, and economic factors (Lambin, et al., 2001; Meyer & Turner, 1994). Economic development activities such as road building can lead to LUCC, whether intentional or not (Cropper, Griffiths, & Mani, 1999; Forman & Alexander, 1998; Geist & Lambin, 2002).

Road network development is usually a result of a public policy to serve several purposes. In most cases, the development of road networks aims to foster social and economic development by increasing linkages within a region, facilitating movement of people, goods, and services. In other cases, such as the Thai-Laos Friendship Road/Bridge, roads were built to enhance the relationships between the neighboring countries, and the Interstate Highway System in the USA was built to support national security (Australian Agency for International Development (AusAID), 2009; Caldwell, 1974; Muscat, 1990).

Although roads are built or enhanced for several purposes, they can drive economic development. In Malaysia, improved roads helped the economy of the local residents increase their household aggregate income by increasing the sales of export crops (e.g. rubber, pepper, and cocoa) (Windle & Cramb, 1997). On the other hand, in developed countries such as the USA or in Europe, economic activities such as housing development projects often incur road development (Krugman, 1999; Ralston & Barber, 1982; Stanilov, 2003).

Studies such as Geist and Lambin (2002), Vickerman et al. (1999), and Forman and Alexander (1998) have shown that road network development that aims to enhance economic development can result in LUCC. Thus, it is important to understand road and land-cover interactions in terms of the influence of roads on the landscape. Roads influence regional land cover because they enhance access to land for human activities (Nelson & Hellerstein, 1997; Pfaff, 1999). These influences can be, for example, a conversion of forest to agriculture, including both crop cultivation and livestock. In specific regions, road building in northeast Thailand (Panayotou & Sungsuwan, 1994), northern and central Thailand (Cropper, Puri, & Griffiths, 2001a), Belize (Chomitz & Gray, 1996), and Rondônia, Brazil (Alves, Pereira, Sousa, Soares, & Yamaguchi, 1999; Soares-Filho, et al., 2004) led to conversion of forests to crop production or cattle grazing. Initial development of roads in the Rondônian rainforest in Brazil in particular illustrates an increase in access to the rainforest for humans which resulted in a large-scale conversion of forest to agricultural land (Alves, et al., 1999; Stone, Brown, & Woodwell, 1991). Another common landscape transformation that road networks can influence is the conversion of agricultural land to built-up areas, although the literature does not explicitly reflect that roads are the cause of such conversions. Nevertheless, rapid urban growth and conversion of agricultural land to urban areas or built-up areas occur closer to road networks in as disparate locations as the Kansas City Metropolitan area in the central USA (Underhill, 2004), Puerto Rico (López, Aide, & Thomlinson, 2001), and the urban expansion of Beijing (Zhang, Wang, Peng, Gong, & Shi, 2002). Land-cover conversions usually happen along the road network because roads facilitate mobility and access to jobs, markets, or city centers, thus increasing incentives for land conversion.

During the 1980s to early 1990s, Thailand experienced rapid economic growth by transitioning from an agriculture-based economy to a more industrial economy (Dixon, 1999; Yokakul & Zawdie, 2009). Despite the rapid industrial transition, agriculture is still the largest economic sector in terms of workforce (LePoer, 2007). Agriculture expansion in Thailand has moved rapidly towards commercial farming and intensification of cropped area (Ekasingh, Sungkapitux, Kitchaicharoen, & Suebpongsang, 2007; Intarakumnerd, Chairatana, & Tangchitpiboon, 2002). In 1997, the Asian Economic Crisis hit Thailand and reduced the GDP by 9% (Rosegrant & Ringler, 2000). The investment in public infrastructure such as a road network development was delayed during the crisis (Ministry of Construction, 1999). The economy recovered by 2003 but the investment in the transportation sector has never returned to the pre-crisis position (Economic and Social Commission for Asia and the Pacific (ESCAP), 2005, 2009).

Notwithstanding the downturn in 1997, Thailand's road network had been undergoing extensive development for nearly 60 years as a result of National Economic and Social Development Plans that aim to improve the quality of life through poverty alleviation, enhanced economic development, and increased linkage among different regions (Lop Buri Provincial Office, 2006; Puri, 2006; Rojnkureesatien, 2006). Early studies showed that road network development in Thailand enhanced social and economic development by increasing household income through the production of more cash crops (Dixon, 1999; Hafner, 1970;

Hughes, 1971). Although these social surveys were not spatial in nature, they do note that much of the landscape change was from forested areas to agricultural areas, particularly in the central plain and the northeastern regions.

In Lop Buri, a relatively wealthy agricultural province in the central plain of Thailand and about 150 km north of Bangkok, the road network was intentionally designed to drive economic development. The policy responsible for road network development within the province was initiated in the 1930s by General Por Piboonsongkram, who established Lop Buri City as a military town. The road network was developed to facilitate military movements, to enhance economic and social development, and to increase linkages among other regions of Thailand (Caldwell, 1974; Rojnkureesatien, 2006). Piboonsongkram's policy transformed Lop Buri City to the center of economic development in the upper central region of Thailand (Office of Information and Technology: Thepsatri Rajabhat University, 2008). In the past several decades, Lop Buri province experienced major landscape changes, especially in response to the growth of the economy (Oung-youang, 2000).

The purpose of this study is to describe how the road network that was built intentionally to stimulate economic development influenced more broadly distributed land-cover change in Lop Buri province from 1989 to 2006. This period is chosen because we can compare the amount of the road network development and the amount of land-cover change before and after the economic crisis. This study analyzes the change in the road network development and land cover from 1989-1998 and 1998-2006. This paper describes and explains the patterns of the road network development and land-cover change from 1989 to 2006 in Lop Buri province in Thailand by measuring the spatio-temporal changes in road network and land cover in the region. Specific research questions for this study are: 1) How has the road network developed from 1989-1998 and 1998-2006? 2) How has the land cover changed from 1989-1998 and 1998-2006? and 3) What are the spatial relationships between where roads were developed and where land-cover change occurs? We measured spatial relationships of road network development in terms of distance to roads. As the road network is developed, distance to roads decreases, leading to better accessibility to land. In this study, we presume a direct relationship between the road network development and agriculture expansion as the indicator of the economic development (Alexandratos, 1995)**.** We hypothesize that 1) agriculture expansion occurs closer to roads at the expense of forest cover, and 2) land area closer to roads devoted to food crops (i.e. rice) will be increasingly replaced by cash crops (e.g. cassava, maize, sugarcane).

Data and Methods

The Study Area

Lop Buri province is located in the central region of Thailand approximately 150 km north of Bangkok, the capital city of Thailand, and is a gateway between the northern, central and northeastern regions (Figure 2-1). Lop Buri province is one of the wealthier provinces in Thailand and is ranked 22nd out of 76 provinces in GDP per capita (Lop Buri Provincial Office, 2006). The province's population in 2006 was 839,397. The province consists of 11 districts (called “amphoe” in Thailand). Amphoe Muang Lop Buri (Lop Buri City) is the most populated district with a 2006 population of 249,907 persons. It is followed by Amphoe Chai Badan (Chai Badan

City) with 89,077 persons. These two districts are the most important centers of economic activity in the province.

At approximately 6,300 km^2, the province is ranked 37 out of the 76 provinces of Thailand in land area. It is located between 14º 39′ N and 15º 35′ N latitude and between 100º 24′ E and 101º 26′ E longitude. The elevation ranges from 2 to 840 m above sea level (Figure 2-2). Approximately 65% of the land area is below 100 m above sea level. These low-lying areas are found in the west and scattered among the northeast. Areas of elevation between 100-300 m make up approximately 25% of the province and are scattered in the northern, central, and eastern regions; areas above 300 m make up 10% of the province and are scattered in the central and eastern regions.

Lop Buri has a monsoon climate. The province's rainy season is from May to October, during the southeast monsoon from the Indian Ocean. Rainfall in the province is bimodal. The highest rainfall is in September and the second highest is in May. For the 30-year span from 1961 to 1990, the average May rainfall was 170 millimeters and September rainfall was 280 millimeters. In some years, the intense monsoon causes flooding in the province and reduces road quality and access. During November and April, the province experiences the dry northeast monsoon. Average minimum temperature from 1961-1990 was 23.3 ºC, and the maximum was 33.3 ºC. April is usually the hottest month and December and January are the coldest months.

For the past several decades, the road network in Lop Buri has been developed through road extension, lane-widening, and road surface upgrades. In

2006, Lop Buri had a total road length of 4,727 km. However, road density is not evenly distributed throughout the province. In the lower western and the upper sections, the road network is dense compared to the central and the upper western sections (Figure 2-3). In the eastern section of the province, the road network has been altered due to the construction of Pa Sak Dam. The Pa Sak Dam construction started in 1994 and was completed in 1999.

Data Sources

Satellite images used in this study are Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+) images: 20 January 1989 (TM 4), 10 March 1998 (TM 5), and 8 March 2006 (ETM+). Lop Buri province is covered by two sequential Landsat scenes: path 129 rows 49 and 50. The satellite images were acquired during the dry months (December to April), when clouds are minimal compared to the wet season (May to November).

Road network data were compiled from three different Thai agencies: Department of Highways, The Department of Rural Roads, and Department of Environmental Quality Promotion, and Royal Thai Survey Department. They were geo-referenced to Landsat images with a root mean square (RMS) error of <15 m. Ancillary data such as topographic maps and aerial photographs were used to help geo-reference the road networks.

A total of 352 training samples, which were used for land-cover classification and accuracy assessment, were collected during the field visits. Between 30 and 60 samples were collected for each land-cover class by using spatially random sampling.

Land-Cover Classification

The satellite images were geometrically aligned using image-to-image transformations and the nearest-neighbor algorithm. The base for registration were two rectified and mosaicked ETM+ scenes acquired November 2, 2000 and rectified with 67 ground control points at road intersections and bridges, collected with hand-held GPS receivers. All points were collected with 7-12 m position errors, and the RMS error of the original transformation was approximately 12 m. All image-to-image transformations had a root mean square (RMS) error <15 m. The image of 1989 has approximately 4% cloud cover. Clouds and shadows were treated as no data and are excluded from the analysis. The cloud cover areas of image dates 1998 and 2006 were eliminated on the corresponding areas of 1989 image.

The training samples collected were randomly divided into two equal sets: one for land-cover classification and the other for accuracy assessment. Satellite images for each time step were classified into six land-cover classes with a hybrid approach including unsupervised classification, supervised classification, and rule-based methods. The classes are forest (F), water (W), plantation (P), rice (R), upland crops (UC), and built-up (BU). The definitions of these land-cover types are explained in Table 2-1. These classes are chosen because they represent the dominant or economically important land covers in Lop Buri province. In addition, Google Earth was used to identify land-covers visually and help with the classification processes. Our knowledge of the study site and visual interpretation were also incorporated and helped to classify the images to ensure the high accuracy of the land-cover classification. An accuracy assessment was performed for the 2006 classified image. The overall classification accuracy image was 83.21% with a kappa statistic of 0.78 (Table 2-2). Accuracy assessments for the earlier image dates were not conducted in absence of land cover data for earlier dates.

Change Trajectory Analysis

Change trajectory, a post-classification pixel-by-pixel comparison method was used to determine spatial and temporal patterns of change of each land-cover type (Lu, Mausel, Brondízio, & Moran, 2004; Mertens & Lambin, 2000; Singh, 1989). The number of trajectories was based on the number of the land-cover classes and the number of dates analyzed. Only land-cover trajectories that are greater than 1% of the landscape are shown in the results section.

Road Network Analysis

The road network analyzed in the study includes both hard and loose surface roads. We excluded cart tracks from the analysis. The majority of the roads in the province were built and maintained by the Department of Highways and the Department of Rural Roads.

We calculated Euclidean distance from roads to determine the spatial relationship between the road network and land-cover distribution. Roads up to 6 km outside the Lop Buri provincial boundary were also included, although they are not shown on the maps. This procedure eliminated the edge effect of the provincial boundary. The land-cover distribution is analyzed for segments of every 100 m to the nearest roads.

Next, land-cover change trajectories were split into two time steps: 1989-1998 and 1998-2006. The 1998 road network was used to study the land-cover change trajectories for 1989-1998 and the 2006 road network was used to study the land-cover change trajectories 1998-2006. Note that the Asian Financial Crisis occurred in 1997, just before the acquisition of the 1998 image.

Results

Land-Cover Distribution

Lop Buri is largely covered by agricultural areas, particular rice and upland crops with upland crops being the most dominant land-cover in the landscape. The area occupied by upland crops increased from 38% in 1989 to 51%, and 57% respectively for 1998, and 2006 (Figures 2-5 and 2-6). Upland crops are mostly located at elevation > 20 m and at a gentle slope. Rice paddies reduced from 24% in 1989 to18%, and to 17% respectively for 1998, and 2006. Rice is mostly found in low elevations (< 20 m) where slopes are gentle or the land is flat. Moreover, rice growing areas are largely concentrated in the southwest of the province; however, some rice paddies are found scattered at the higher elevations. Forest is the second largest type of land-cover in 1989 (34%). The forested areas declined from 34% of the province in 1989 to 26% in 1998 and 18% in 2006. In 2006, forested areas and upland crops area had approximately the same percentage, i.e. 18% for forest and 17% for upland crops. Forests are primarily located at high elevation (> 300 m), steep slopes, and along rivers in lower elevations. Plantation, teak and eucalyptus has the lowest areal extent in the landscape; however, they have become evident in the landscape. Plantation has increased from 0% to 0.17% during 1989 to 2006, scattered throughout the province. Built-up area has increased from 3% to 5% and to 6% for 1989, 1998, and 2006 respectively. Built-up areas are largely concentrated along major roads and existing towns. Water area in 1989 was 0.5% and reduced to 0.4% in 1998, before increasing to 2.5% in 2006 with the construction of the Pa Sak

Dam in the south-central part of the province. Finally, the general landscape patterns for the 18-year period showed that the landscape is more fragmented in 1989, particularly with patches of forests and rice distributed around the province. In 2006, the landscape has become more homogenous with upland crops dominating.

Land-Cover Trajectories

Land-cover change trajectories of the years 1989, 1998 and 2006 are compared on a pixel-by-pixel basis to examine the possible land-cover changes. Two-date change trajectories are analyzed in this paper. There are 36 possible trajectories in the 2-date change, but only the 13 trajectories that each represent >1% of the landscape will be described.

Figure 2-7 and Table 2-3 illustrate the two-date land-cover trajectories findings. The results show that more than 50% of the landscape remains unchanged. On the other hand, nearly 48% of the landscape did undergo a change. Upland crops-upland crops (UC-UC) remains the largest percentage of unchanged trajectory for the both the first time period (1989-1998) and the second time period (1998-2006) with 29% for 1989-1998 and 45% for 1998-2006. Forest-forest (F-F) has the second highest percentage of unchanged trajectory for each time period. F-F was 17% between 1989-1998 and 14% between 1998-2006. Rice-rice (R-R) is quite stable during both time periods and occupied approximately 13% of the landscape. Of the trajectories that represent land-cover change in Lop Buri, the most extensive are from forest to upland crops (F-UC), rice to upland crops (R-UC), forest to rice (F-R), and upland crops to built-up (UC-BU). F-UC, which comprises the largest change trajectory, covered 13.75% and 8.65% of the landscape for 1989-1998 and 1998-2006. The second largest change was R-UC with 7.63% between 1989-1998 and

2.57% between 1998-2006. Next, the rate of change from F-R was fairly steady for the two time periods: 2.41% between 1989-1998 and 2.04% between 1998-2006. Finally, UC-BU has increased from 1.1% in between 1989-1998 to 1.63% between 1998-2006.

Road Network Distribution

In general, the road network in Lop Buri across the three dates was distributed throughout the province except around the mountains (Figure 2-3). The total road network lengths were 3,246 km, 4,549 km, and 4,725 km for 1989, 1998, and 2006, respectively. The increase of road length during the 1989-1998 time period was higher than 1998-2006. The increase of the road lengths was mostly located in the northern two-thirds of the province.

Euclidean distance created from these three dates showed that the maximum distance to any road across three dates was 6.89 km. The farthest distance to any roads was located in the forested areas and the Sab Langaka Wildlife Sanctuary. The average distance to roads was 1 km, 0.78 km and 0.72 km, respectively for 1989, 1998, and 2006.

Spatial Relationship between the Road Network and Land-Cover Distribution

As noted above, the most remote distance to roads from any point within the province was around 7 km. Across the three dates, the general spatial pattern of land cover and distance to roads indicated that forested area increased steadily as the distance to roads increased. At a distance beyond 6 km, the amount of forest was not affected by the distance and steadily remained as the dominant land cover of more than 90% of the distant land (Figure 2-8). However, within 1 km of roads, the forested area declined significantly from 1989 to 1998 and to 2006.

Upland crops dominated the landscape at a distance up to nearly 2 km. This type of land cover steadily declined as the distance increased from roads. At a distance beyond 6 km, the amount of upland crops declined to less than 10%. In 1989, upland crops were the dominant land cover to a distance of 1.4 km, increasing to a distance of 1.7 km in 1998, and to 1.8 km in 2006.

The extent of rice cultivation areas generally decreased further away from roads. No rice cultivation area was found at a distance beyond 6 km in 1998 and 2006 and less than 2% in 1989. In 1989, the amount of rice cultivation area covered approximately 25% of the landscape within 2 km from the nearest road. Rice then declined with increasing distance. In 1998 and 2006, rice cultivated areas were reduced within a distance of 1.5 km and 1.2 km.

Built-up areas were generally found within 100 m of roads. The extent of built-up areas increased from 25% to 26% to 30% respectively in that first 100 m for 1989, 1998, and 2006. Beyond this distance, it declined sharply to less than 2% across the three dates. The amount of built-up areas approaches zero at distances beyond 6 km.

Spatial Relationship between the Road Network and Land-Cover Change

The road network development, in terms of total length, was more extensive between 1989-1998 than between 1998-2006 (see Section 3.3). Road network development during 1989-1998 occurred mostly in the northern two-thirds of the province. By overlaying the road network development maps on the land-cover classifications (Figures 2-3 and 2-5), the data show that in the first period these roads were extended and upgraded mostly in agricultural areas where rice and upland crops are mainly present. In contrast, between 1998-2006, the road network development occurred not only mostly in agricultural areas but also along the edge of the mountains where the landscape is covered by forests.

Road development and the observed land-cover trajectories are clearly linked. Between 1989-1998, the extent of road increase was 1,303 km and 176 km in 1998-2006 (Table 2-3). Results show that the amount of change captured by the land-cover trajectories reflects the extent of road network development. For example, 13.75% of the study area was converted from forest to upland crops (F-UC) between 1989-1998; whereas only 8.65% between 1998-2006. Rice to upland crops (R-UC), and forest to rice (F-R) also followed this trend.

The relationship between land-cover change and distance to roads for each time period is shown in Figure 2-9. Only the four major trajectories covering extensive proportions of the study area are described and shown. These trajectories are forest to upland crops (F-UC), rice to upland crops (R-UC), forest to rice (F-R), and upland crops to built-up (UC-BU). The changes to rice paddies and upland crop production (e.g. cassava, maize, sugarcane, and sunflowers) were mainly associated with crops known to be grown commercially. Moreover, the areas of each of these trajectories tended to decline as the distance to roads increases. Overall, these land-conversion types were rare beyond 6 km from roads.

Firstly, F-UC change was steady at a distance within 2 km of roads and then decreases as the distance increases. The amount of F-UC between 1989-1998 was higher than 1998-2006, that is, up to 15% and 11% within the first 6 km of roads, respectively. This type of land cover conversion was not found beyond 6 km. Secondly, R-UC had a similar pattern as F-UC, that is, the conversion was less common further away from roads. R-UC between 1989-1998 declined within a distance of 3 km, but then was quite steady at the distance between 3-5 km. However, between 1998-2006, R-UC had a different pattern. R-UC started to increase at a distance of 3 km and peaked at 5-6 km. Of these two time periods, R-UC was not found at a distance beyond 6 km and the amount of R-UC was also higher in 1989-1998 than 1998-2006, up to 10% and 4% respectively. Thirdly, F-R did not differ much between the 1989-1998 and 1998-2006. The trajectory change is below 3% within a distance of 6 km. This type of land-cover trajectory was not found at a distance beyond 6 km. Lastly, UC-BU remained steady for both 1989-1998 and 1998-2006. It was mainly found at 100 m from roads for both 1989-1998 and 1998-2006, with a trajectory change of approximately 5%. At a distance beyond 100 m, UC-BU dropped sharply to around 1% and reached zero percent beyond 6 km.

In summary, our research found that landscape change in Lop Buri province comprised mainly forests to upland crops, rice to upland crops, forest to rice, and upland crops to built-up during 1989-2006. There was a general trend for greater percentages of these types of land-cover conversion between 1989-1998 than between 1998-2006. This was related to the extent of road development. Road network was developed more extensively between 1989-1998 compared to 1998-2006. Lastly, the spatial relationships between distance to roads and land-cover change indicate that land-cover changes occurred within 6 km of roads.

Discussion

The results show that the two hypotheses stated in the introduction are supported. The total land-cover change in Lop Buri was large with 48% change between 1989-2006. The dominant land-cover change in Lop Buri was an increase in upland crops and decrease in forest cover (i.e. forest-agriculture conversion). Another important land cover change in the region was the decrease in rice paddies, which were replaced by upland crops (e.g. conversion from food to cash crops). Lastly, upland crops were also replaced by built areas in the landscape. Our findings show a similar pattern of land-cover change, especially from forest to agriculture, as those found elsewhere in Thailand. For example, in Nang Rong District in the Northeast, Walsh et al. (2001) found that between 1972-1997, forest had declined across 12.75% of the study area while agriculture increased across 20.3% of the study area. Likewise, in Ban Don Bay in the South, forested areas were transformed to agricultural areas, particularly for shrimp farming. This accounted for about 15.2% of the total land area (Muttitanon & Tripathi, 2005). However, though within the same country, different drivers affected the extent of land-cover change at each locale. In the case of Nang Rong, major driving factors are population, roads and elevation (Walsh, et al., 2001), whereas in Ban Don Bay, poor enforcement of laws and high profits from shrimp farming are the major causes of land-cover change (Muttitanon & Tripathi, 2005). Hence, Lop Buri can be considered as one of the most extensively changed landscapes in Thailand.

The largest permanent land cover types in Lop Buri were upland crops, followed by forest and rice. Most of the permanent forest cover in the province was found on high elevations and in the protected area of Sablangka Wildlife Sanctuary (SWS)**.** A large percentage of unchanged, permanent forest cover inside the SWS, with forest cover declining outside, as is the case for the SWS, is a pattern common in many tropical forests in developing countries (DeFries, Hansen, Newton, &

Hansen, 2005). In addition, the biophysical features such as steeper slopes and higher elevations help protect forest from clearing (Cropper, Puri, & Griffiths, 2001b), which may be the reason that most of the forest in higher elevation areas in Lop Buri province is maintained. Although the forest cover in Lop Buri has been maintained inside the SWS and some higher elevation and steep slope areas, a large percentage of this forest cover outside SWS and lower elevation areas has been replaced by upland crops and rice. The large-scale conversions of forest area to upland crops and rice in Lop Buri are shown through the 2-date trajectories: F-UC and R-UC. Agricultural expansion has been cited as one of the most important proximate drivers of forest-cover decline, particularly in developing countries such as Thailand, where agriculture is the main economic sector. This pattern seems to be true for Lop Buri province as well (Cropper & Griffiths, 1994; Marston, Knox, & Liverman, 2005).

Another significant change in Lop Buri was the change in cropping pattern. Rice was increasingly being replaced by upland crops (R-UC). The R-UC change mostly occurred in the upland areas where there were no irrigation services and farmers had to rely on rain (personal interview) (Figure 2-5). However, in the irrigated lowlands, rice remained unchanged. During the 1990s, rice prices declined and became unprofitable because of a decrease in available resources (labor force and water). The Thai government responded to these problems by launching the agricultural diversification policy. The policy encourages farmers to adopt other alternative crops to rice to increase their household incomes. Thus, many rice farmers converted rice paddies to upland crop fields (Cheyroux, 2003; Schar, 2004;

Sirisup & Kammeier, 2003). At the same time, since the mid 1960s, the area under cash crops has expanded as a response to demand from foreign markets, particularly in Europe (Entwisle, Rindfuss, Walsh, & Page, 2008; Phantumvanit & Sathirathai, 1988; Schar, 2004). Lop Buri, among other provinces in the central plain, is a suitable location for producing upland crops because of its proximity to Bangkok and other large metropolitan agglomerations, from where most crops are being exported to international markets (Schar, 2004; Sirisup & Kammeier, 2003).

Globally, one of the indicators of economic growth has been the trend in developing countries for the conversion of staple crops (rice) to cash crops (upland crops) (Ducourtieux, Visonnavong, & Rossard, 2006; Krongkaew, 1985). The replacement of forest cover by upland crops, rice by upland crops and the upland crops by built-up areas in Lop Buri can be taken as an indicator of economic development (Fox & Vogler, 2005; Ramankutty & Foley, 1999). This pattern has been accelerated since the 1960s because road construction policies and the First National Plan became effective (Krongkaew, 1985; Rojnkureesatien, 2006). During the 1960s, agricultural production in Thailand increased at a rate of 7.9% per annum and poverty fell from 61% to 41% by the end of that decade, and to 12.7% in 1996 (Fan, Jitsuchon, & Methakunnavut, 2004; Krongkaew, 1985). Moreover, these land-cover conversions should not be considered as individual processes; instead, they are interlinked parts of a larger system where the land cover along a trajectory of economic development passes through phases of resource extraction from wilderness (e.g. forests), agricultural expansion, industrialization and urbanization (Mustard, DeFries, Fisher, & Moran, 2004). Not only do the land-cover changes suggest economic development, but also the spatio-temporal relationship between the road network and land-cover changes suggests that the intentionally developed road network designed to stimulate economic development in Lop Buri province was the major driver of its LUCC (Hughes, 1971; Krongkaew, 1985).

The spatial relationships between land-cover change and road development show that the areas that were closer to roads had a higher percentage of upland crops, rice and built-up areas. In 1989, upland crop dominated the landscape to a distance of 1.4 km from road. However, in 1998, the domination of upland crops stretched to a distance of 1.7 km and even further in 2006 at 1.8 km (Figures 2-8 a-c). This suggests that road development helped people have easier access to the landscape and facilitated land conversion (Arima, Walker, Perz, & Caldas, 2005; Nelson & Hellerstein, 1997; Perz, Caldas, Walker, Arima, & Souza, 2008). This argument is supported by our results that, from 1989 to 1998 and to 2006, the total forested area had declined. Most of these declines were due to the increase in upland crops (F-UC). Forest cover increased and conversion to upland crops decreased, as the distance from roads increased.

The overall extent of land-cover change is reflected by the extent of roads developed. The road network in Lop Buri was more extensively developed between 1989-1998 than between 1998-2006. During the early 1990s, Thailand’s economy was prosperous and investments in the road network development were substantial. However, in 1997, the Asian Economic Crisis occurred and road development investment projects declined drastically (Department of Highways, 2007; Ministry of

Construction, 1999). The response to more roads developed between 1989-1998 was increased land cover conversion (e.g. F-UC, and R-UC) during this period.

The results suggest that the Thailand government has largely achieved its goals of road development to foster economic opportunities in rural areas such as in Lop Buri province. Fan et al. (2004) estimated that every one million baht (approx. $33,000 US) spent on road investment reduced the number of rural poor by 107. Economic development in Lop Buri was largely indicated by land conversion from forest to upland crops as well as upland crops to built-up areas. Road network development in Lop Buri increased the economic opportunities by allowing farmers to have better access to larger market areas such as Bangkok or Chiang Mai to sell their agricultural commodities. Furthermore, it helped rural farmers to engage in nonfarm employment opportunities such as food processing enterprises, electronic repair shops, and restaurant services (Fan, et al., 2004). This is because development of the road network reduced the transportation costs as well as the travel time for the commodities to be transported to these major markets (Buurman & Rietveld, 1999; Rodrigue, Comtois, & Slack, 2009; Wilkie, Shaw, Rotberg, Morelli, & Auzel, 2000).

The land-cover changes experienced in Lop Buri suggest that road development more generally plays a major role in economic development and can lead to land-cover transformations. This study has shown that the road network development in Lop Buri is linked to economic development. This study analyzed the spatial and temporal inter-relationship of land-cover change and road development. However, road network development may not be the only factor that contributes to land-cover change. Land-cover change usually results from the combination of multiple biophysical, economic, social, and political drivers such as income, rainfall, and population dynamics (Geist & Lambin, 2002). Also, information on the characteristics of roads, such as accessibility, connectivity, road type, and road pattern is needed for further investigation as these characteristics might play a role in land-cover change.

This study examined the influence of road network development on land-cover change in Lop Buri province from 1989 to 2006 by using remote sensing and GIS to focus on the spatial and temporal relationships between land cover and roads. With economic growth in a developing region like Lop Buri province, land-cover change is a major contributor to local environmental change. While the majority of landscape remains as upland crops, the change to upland crops is increasing with economic opportunities enhanced by road development. The loss of forested areas to upland crops and other land cover types seen in Lop Buri can lead to: change in local climate (Dale, 1997), change in local hydrology (Bruijnzeel, 2004), loss of biodiversity (Kummer & Turner, 1994), and loss of soil resources (Kummer & Turner, 1994). However, we have yet to assess the extent to which roads, economic development, and land-cover change contribute to these consequences.

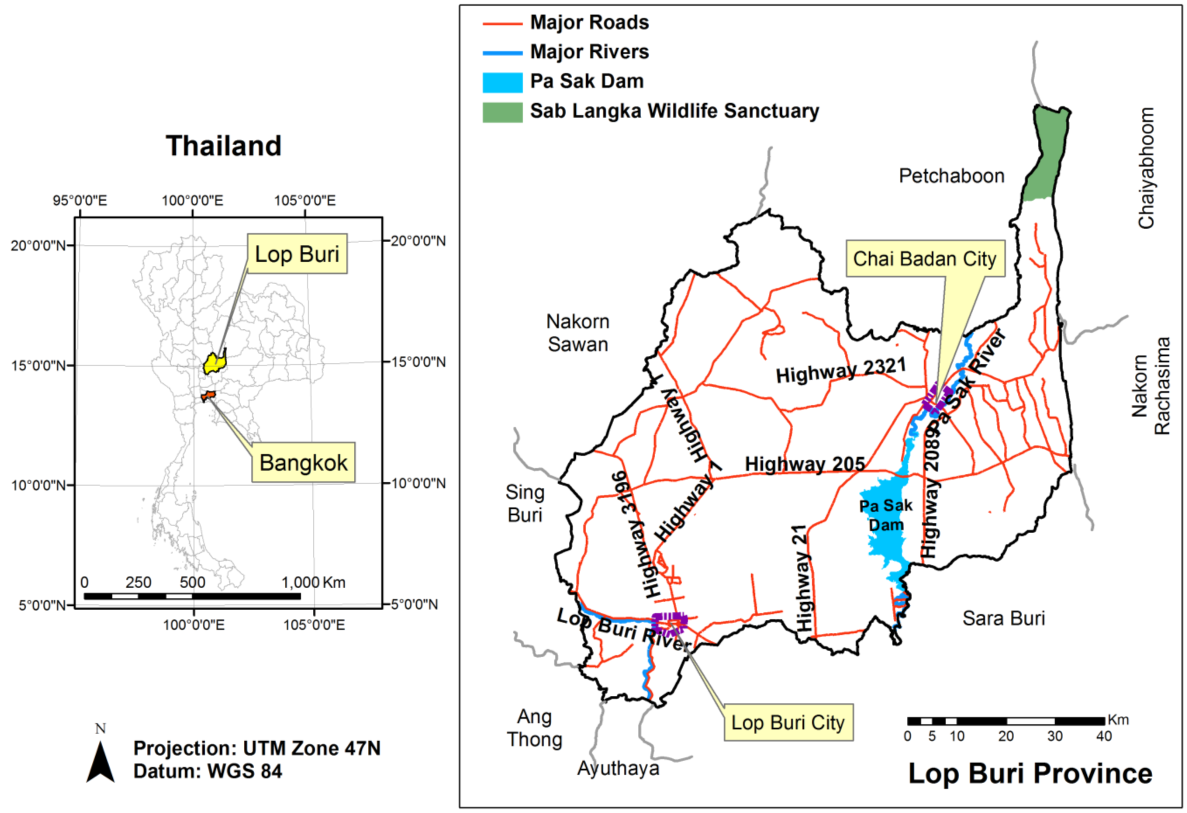


Figure 2-1. Location map and major roads of Lop Buri province, Thailand.

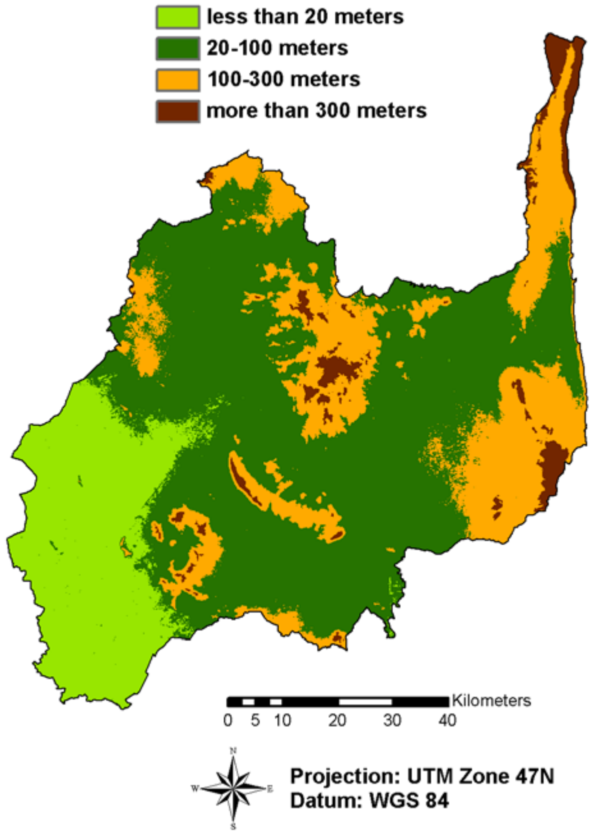


Figure 2-2. Elevation zones of Lop Buri province, Thailand. The western half of the province is in the Chao Phraya River basin, and the eastern half is in the Pa Sak River basin.

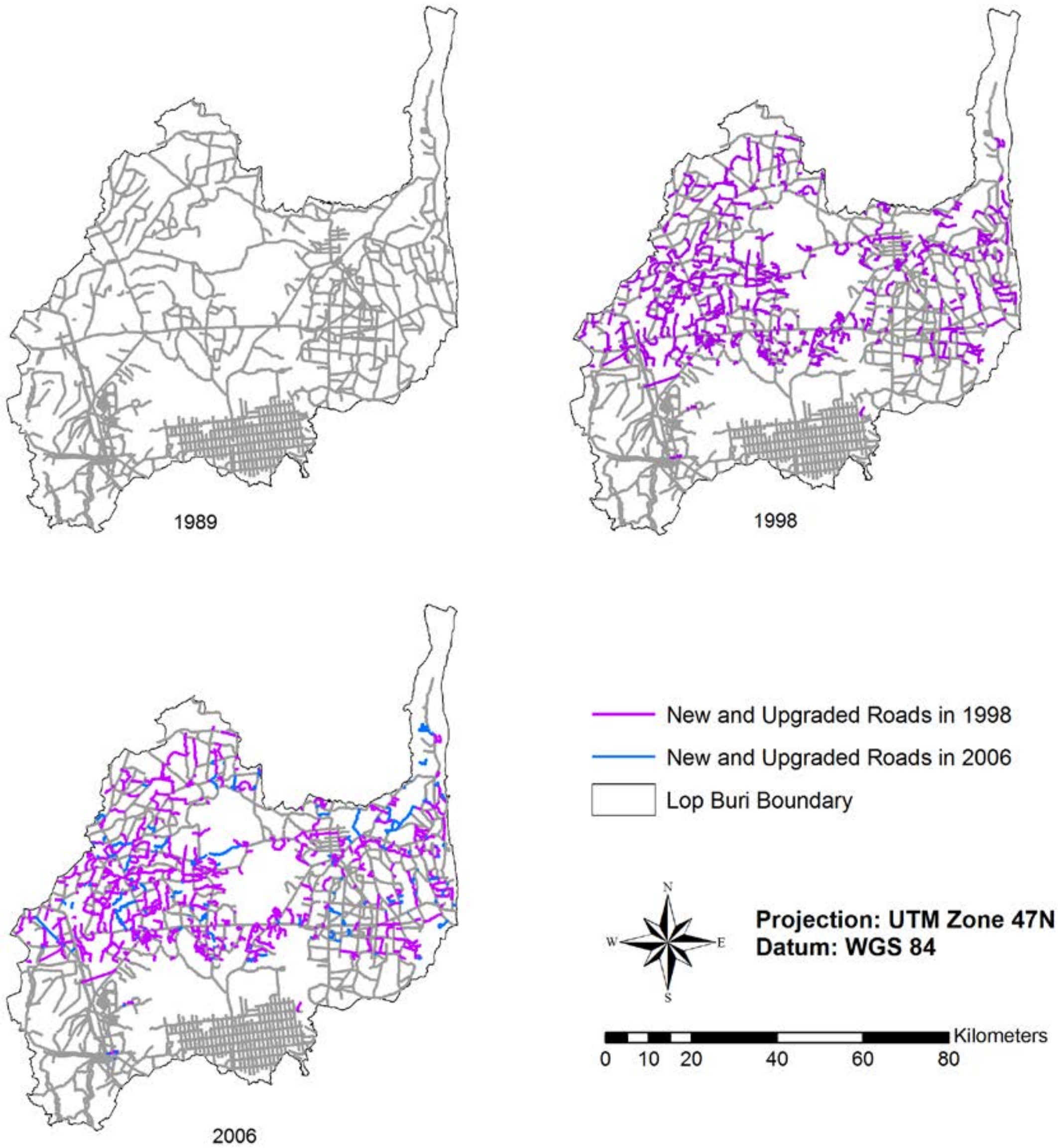


Figure 2-3. Road network distribution in Lop Buri province for 1989, 1998, and 2006.

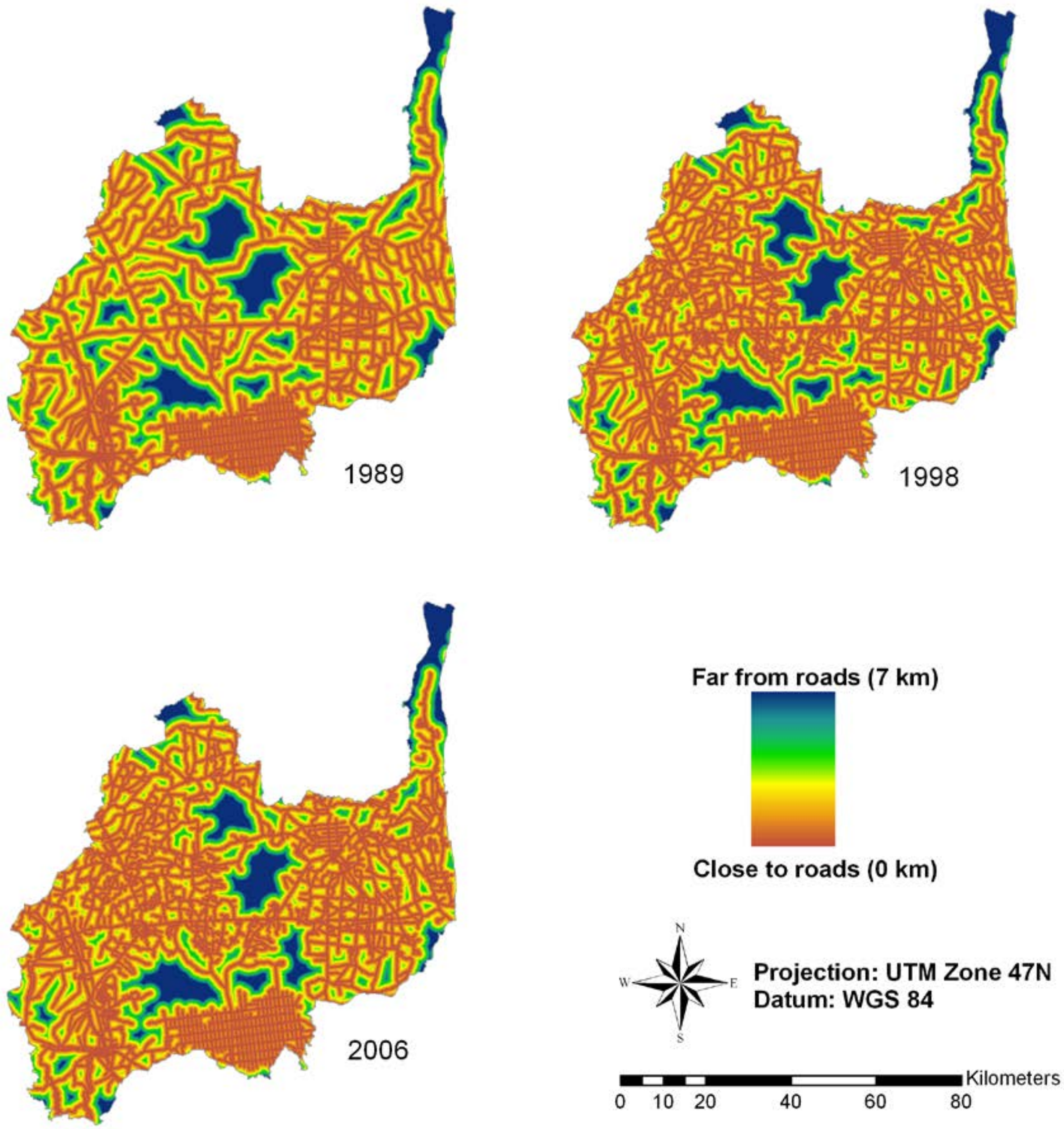


Figure 2-4. Euclidean distance of the road network in Lop Buri: 1998, and 2006. The distance calculation included all roads outside the boundaries of the province within 6 km.

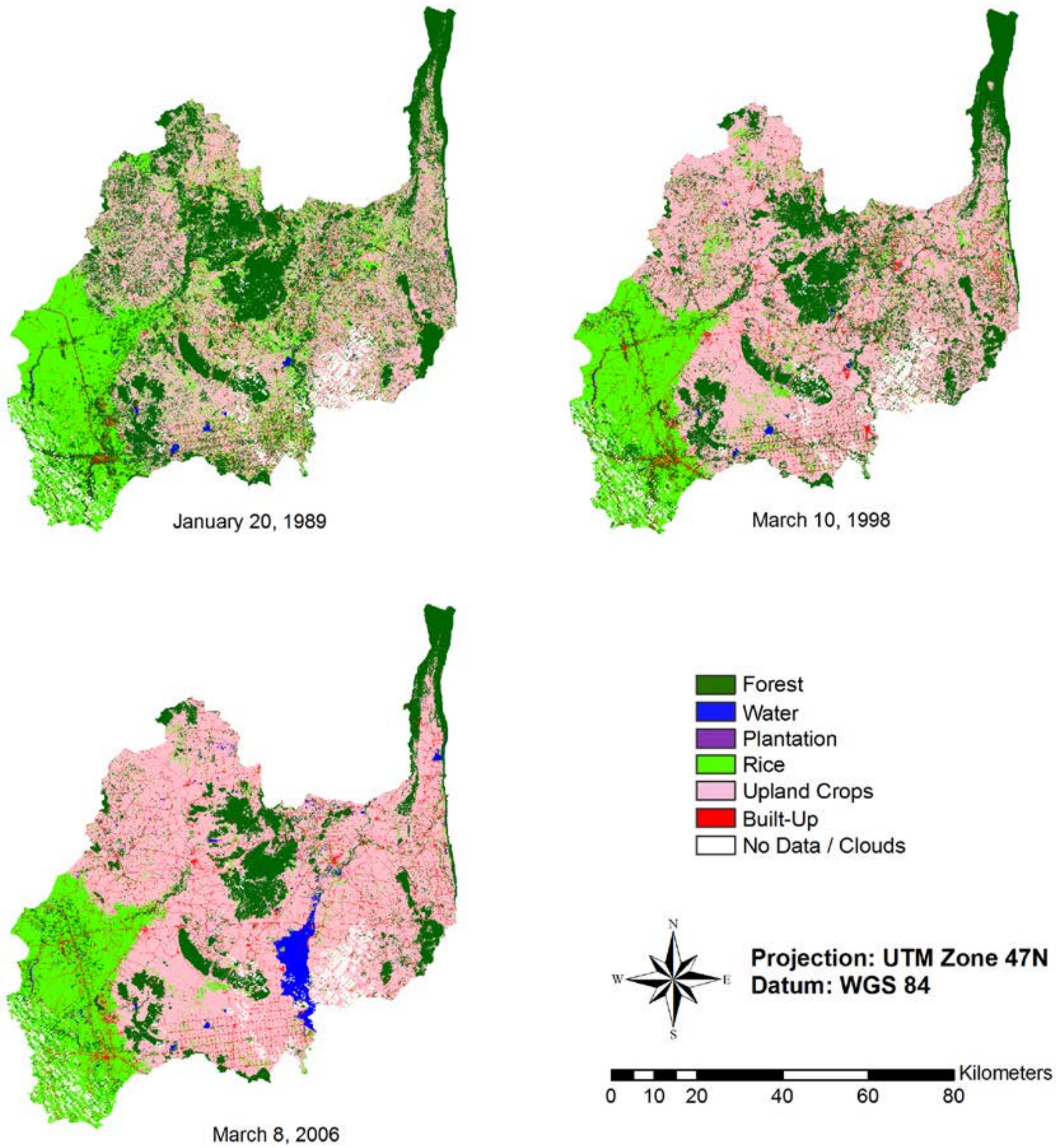


Figure 2-5. Land-cover classification Lop Buri: 1989, 1998, and 2006.

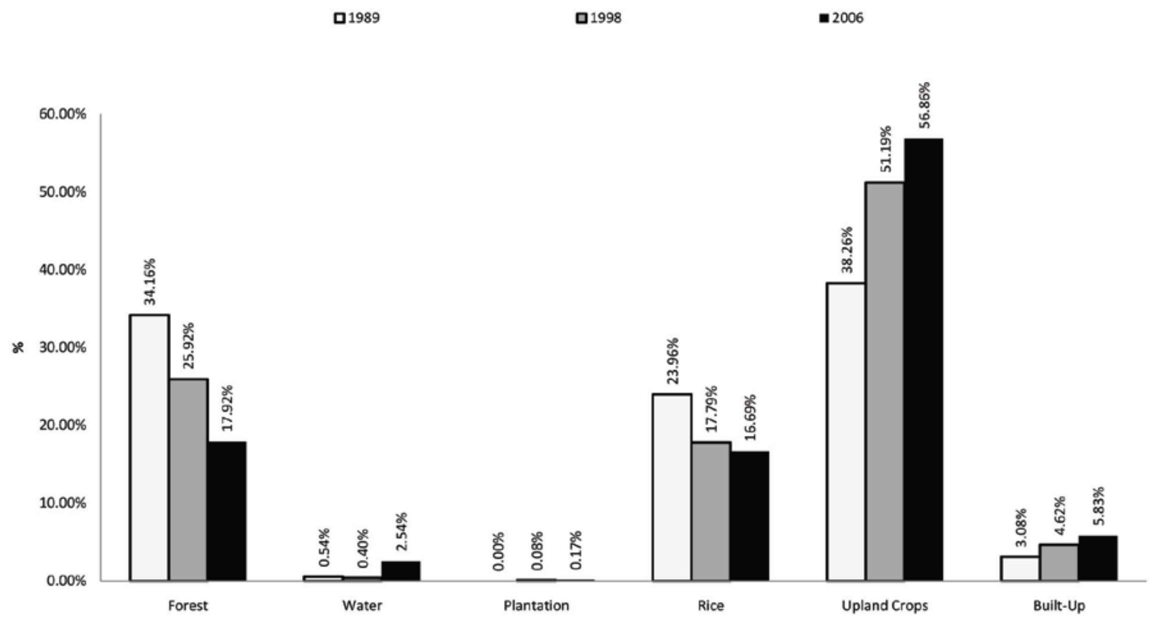


Figure 2-6. Land-cover distribution in Lop Buri: 1989, 1998, and 2006.

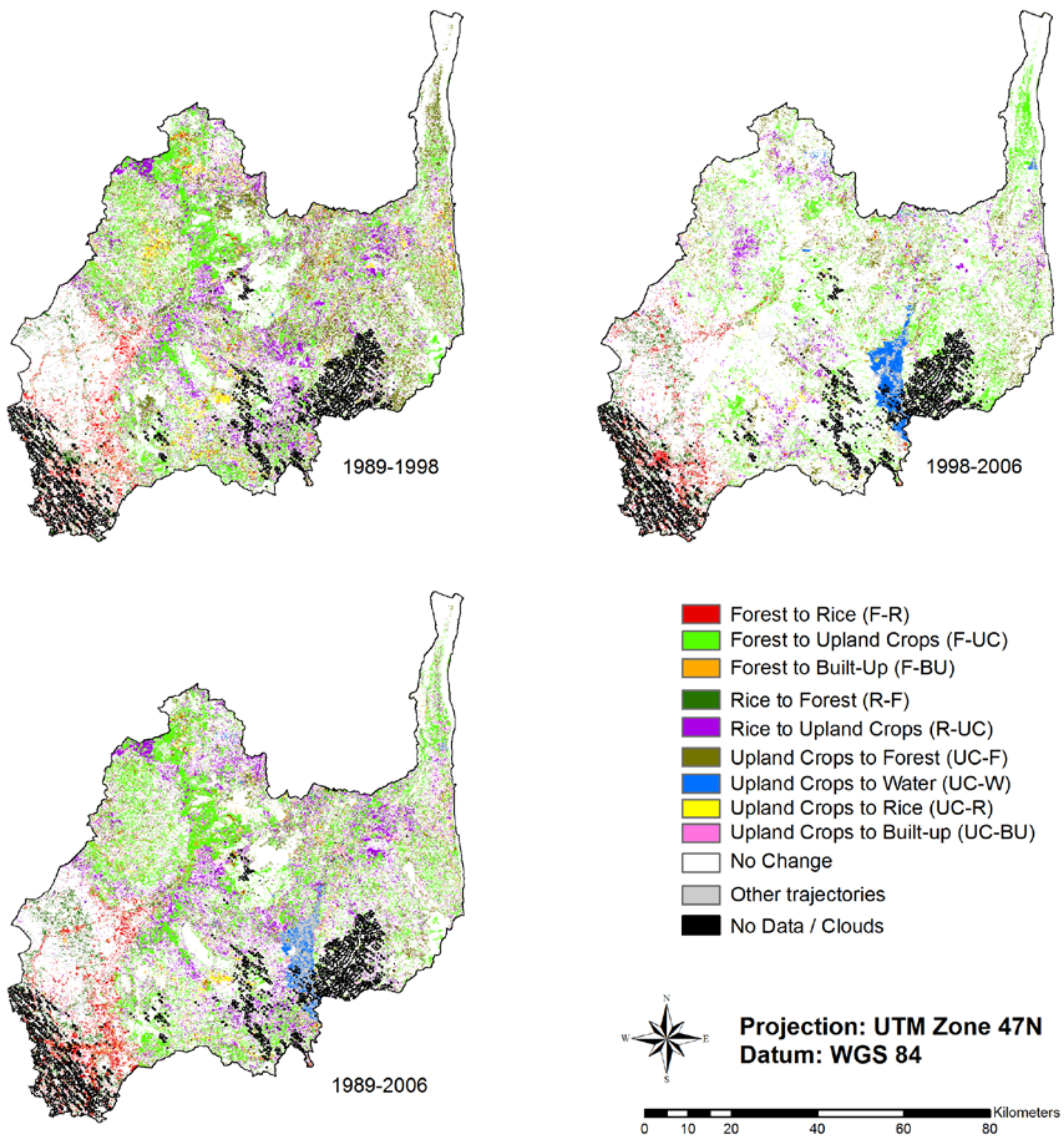
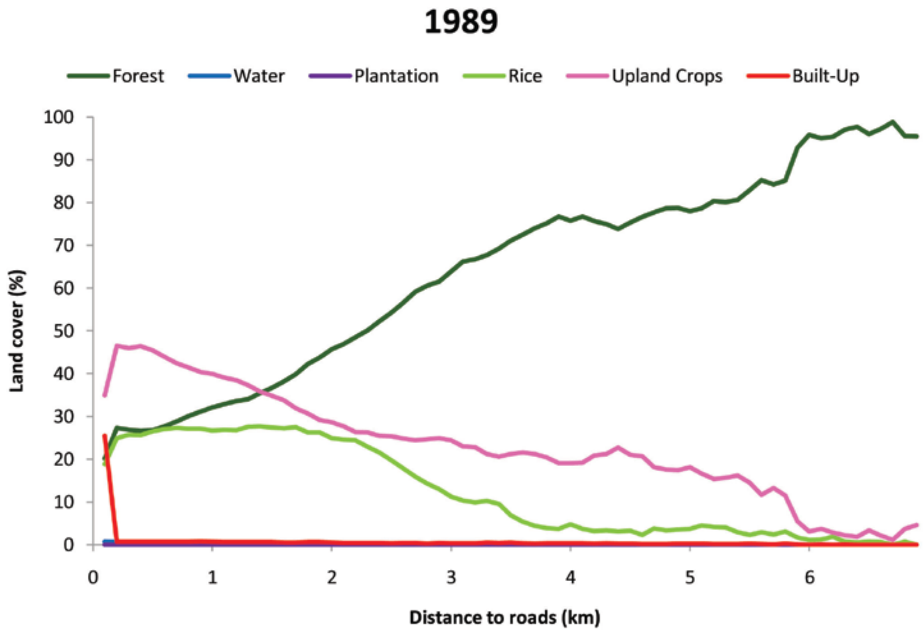
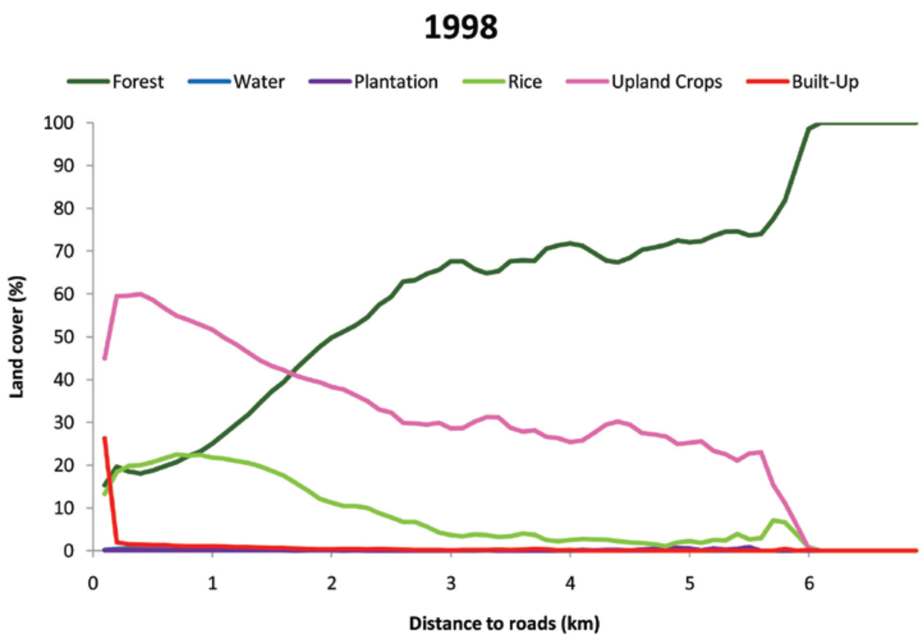


Figure 2-7. Two-date land-cover change trajectories for Lop Buri. F is forest, W is water, R is rice, UC is upland crops, and BU is built-up.

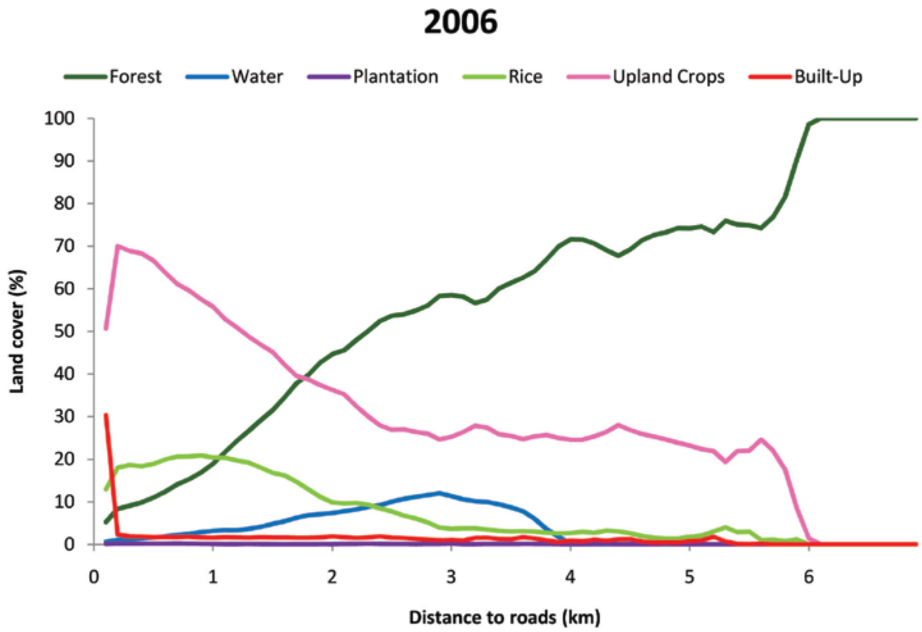


(a)



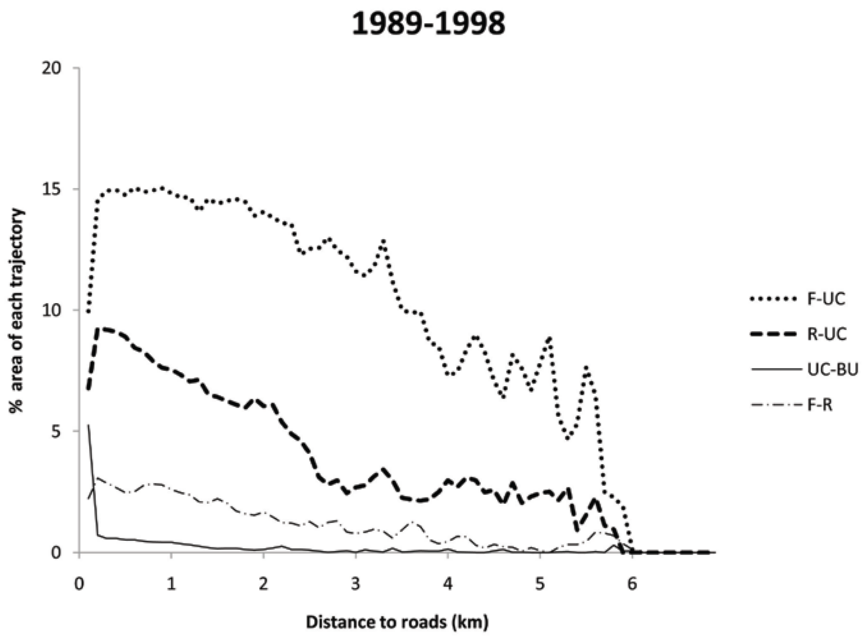
(b)

Figure 2-8. Land-cover distribution according to distance to roads in 100-m zones: (a) in 1989, (b) in 1998, (c) in 2006.

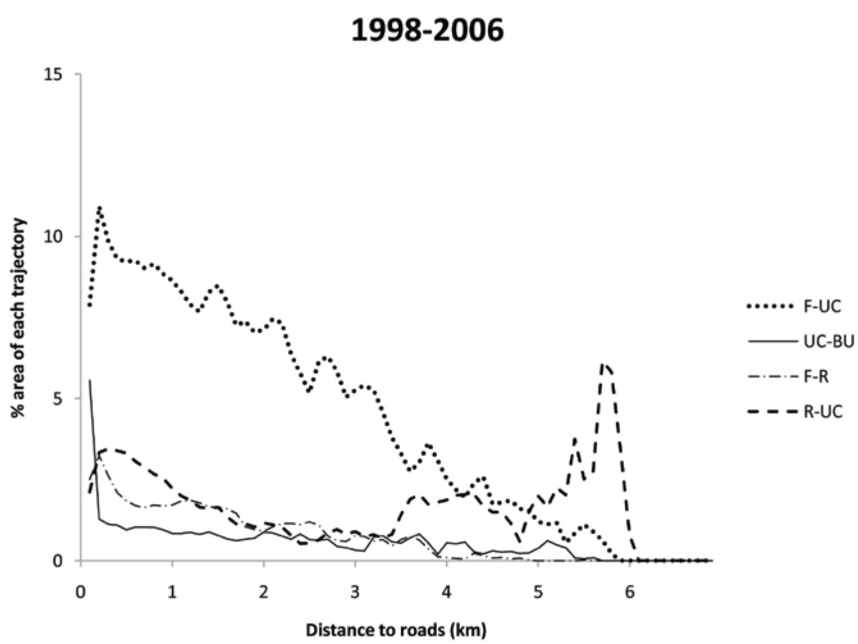


(c)

Figure 2-8. Continued



(a)



(b)

Figure 2-9. Land-cover trajectories for F-UC, R-UC, UC-BU and F-R, and distance to roads in 100-m zones: (a) Land-cover trajectories between 1989-1998 according to distance to roads in 1998, (b) Land-cover trajectories between 1998-2006 according to distance to roads in 2006.

Table 2-1. Description of land-cover classes.

Land Cover	Description
Forest (F)	Areas with trees > 2 meters tall and the canopy cover > 80%.
Water (W)	Water bodies including lakes, reservoirs, rivers, ponds.
Plantation (P)	Includes eucalyptus and teak; the canopy cover < 80%.
Rice (R)	Rice paddies; include upland and lowland.
Upland Crops (UC)	Other crops that are not rice; these include cassava, sugarcane, sunflowers, and maize.
Built-Up (BU)	Include urban areas, residential areas, roads, industrial sites, and construction sites.

Table 2-2. Accuracy assessment for land-cover classification.

		Ground Reference Test						
		Forest	Water	Plantation	Rice	Upland Crops	Built-Up	Users Accuracy
Land-Cover Classification	Forest	30	0	0	3	5	1	76.92%
	Water	0	6	0	0	0	0	100.00%
	Plantation	0	0	21	0	0	0	100.00%
	Rice	2	0	1	34	0	0	91.89%
	Upland Crops	3	0	2	1	92	0	91.09%
	Built-Up	1	0	0	4	6	40	74.07%
	Producers Accuracy	78.95%	100.00%	75.00%	77.27%	86.79%	86.96%	83.21%

Table 2-3. Land-cover trajectories and percent change during the two periods and the entire study time. The abbreviations are as in Table 2-1.

Land-Cover Trajectories	% of the total area 1989-1998	% of the total area 1998-2006	% of the total area 1989-2006
No Change			
UC-UC	28.99	44.56	32.87
F-F	17.21	13.97	13.98
R-R	13.36	13.25	12.66
BU-BU	2.09	3.09	2.15
Changed			
F-UC	13.75	8.65	15.28
R-UC	7.63	2.57	7.83
UC-F	6.29	2.58	1.94
F-R	2.41	2.04	2.89
R-F	2.10	1.24	1.83
UC-R	1.80	< 1	< 1
UC-BU	1.10	1.63	1.65
UC-W	< 1	1.48	< 1
F-BU	< 1	< 1	1.08
Other trajectories < 1%	3.27	4.95	5.83
Increased in total road length (km)	1,303.00	176.00	1,479.00

Note: Total road length in 1989 = 3,246 km ; 1998 = 4,549 km; and 2006 = 4,725 km.

CHAPTER 3
SPATIAL MODELING OF ROAD NETWORK DEVELOPMENT, POPULATION PRESSURE, AND BIOPHYSICAL PROPERTIES OF UPLAND CROP AND FOREST CONVERSIONS IN LOP BURI PROVINCE, THAILAND, 1989-2006

Land-cover change has become one of the world's major environmental concerns. Land-cover change is dominated by human activities and complex spatio-temporal dynamics and interactions between humans and their physical environment. It often leads to intricate landscape mosaics and complex mixtures of land-cover types (Hu & Lo, 2007; Mertens & Lambin, 1997). Several studies have shown that land-cover change can dramatically affect regional climate systems (Dale, 1997; Randall, et al., 2007; Taylor, Lambin, Stephenne, Harding, & Essery, 2002), hydrological systems (Bruijnzeel, 2004; Mendoza, Bocco, López-Granados, & Bravo Espinoza, 2010; Twine, Kucharik, & Foley, 2004), and natural habitats (Homewood, et al., 2001; Serneels & Lambin, 2001a). Many studies in land-cover change have focused on the loss of forests, as removal of forest cover can create negative environmental consequences in relation to changes in carbon storage. It has been shown forests contain approximately 90% of the carbon stored in global vegetation (Dale, 1997). Thus, it is important to understand the process of land-cover change and identify important drivers of change. Spatially explicit modeling of land-cover changes is one way in which scientists can better understand the process of change and quantify change as it relates to the predominant drivers of the process (Serneels & Lambin, 2001b).

In Thailand, rapid land-cover change has occurred over the past several decades, with a considerable loss of forest land. The majority of forest loss is in the Northeast Region, a segment of the country that accounts for roughly 60% of forest loss from 1973 to 1995 (Kermel-Torres, Lauginie, Bruneau, & Dery, 2004). Forested areas were mainly transformed into either agricultural areas or urban settlements. In Lop Buri province, forest loss is mainly associated with rice cultivation and upland crops such as maize, cassava, and sugarcane. Approximately 50% of Lop Buri's original forestland was lost from 1989 to 2006. The decline in forested areas was largely due to the increase of upland crop production (from 38% to 57%) during the same period (Patarasuk & Binford, 2012). Thus, it is necessary to investigate drivers behind these types of land-cover changes and predict the pattern of these changes. One of the approaches that are used for predicting land-cover changes is through a spatial modeling technique.

Previous studies have used various modeling approaches including spatial explicit logistic regression. This technique has been successfully used to determine the driving forces of local and regional land-cover change (Chomitz and Gray, 1996; Braimoh and Onishi, 2007), and is often used to model relationships between land-cover change and drivers based on historical data (Hu & Lo, 2007; Veldkamp & Lambin, 2001). These drivers include biophysical factors (e.g., soil types, elevation, and rainfall), socio-economic factors (e.g., agricultural product prices, population, and land ownership), as well as outcomes of public policy (e.g. road network development, resettlement programs, and agricultural diversification programs). The use of spatial and statistical models have helped to gain an improved understanding of the processes of landscape and land-cover change and its sensitivity to ecological, economic, social, and location-specific factors (Braimoh & Vlek, 2005; Mertens & Lambin, 1997). Thus, modeling techniques are important tools for describing and quantifying the process of change in relation to various drivers and identifying the predominant factors that affect land cover change (Braimoh & Vlek, 2005; Lambin, et al., 1999; Schneider & Pontius, 2001; Serneels & Lambin, 2001b).

The objective here is to examine the relationships between selected biophysical and social factors known to contribute to land-cover change in Lop Buri province, through the development of statistical models to better understand the complexity of land-cover change. This study integrates satellite time-series data, logistic regression, and GIS technology to examine how selected factors related to land-cover change in this region. The major objectives of this analysis are two-fold: (1) to determine the major drivers of land-cover change (as they pertain to upland crop conversion and forest loss) for the periods 1989-1998 and 1998-2006; and (2) to see if drivers vary across trajectories and time. The focus is on the properties and effects of biophysical variables (slope, rainfall, distance to forestland), the potential impact of the road network (e.g., distance to roads, road density), and population pressure (as defined by proximity to major settlements as well as high population density areas). We hypothesize that road network and population pressures are main drivers of land-cover change from 1989 to 2006 in Lop Buri province.

Statistical models were developed for trajectories that changed to upland crops and areas associated with the loss of forests. The trajectories of upland crops and forest loss were the most dominant land-cover changes noticeable in Lop Buri province during 1989-2006. These two types of land-cover trajectories were chosen to reflect areas where the largest amount of land-cover change was occurring (Patarasuk & Binford, 2012). Hence, these trajectories were the major focus of this study. Models of land-cover change were constructed and analyzed, and the results compared for two time periods: 1989-1998 and 1998-2006 using a combination of spatial and non-spatial data. The analysis relied on various descriptive statistics, correlations, and logistic regressions to determine the importance of various drivers of land-cover change. More detail on how the independent variables were derived is given in the methods section.

Study Area

Lop Buri province is situated in the central region of Thailand (Figure 3-1). It is located between 14º39′N and 15º35′N latitude and 100º24′E and 101º26′E longitude. It is an area covering approximately 6,600 km^2. The province is approximately 150 km from Bangkok, the capital city of Thailand. Lop Buri province had a population of 753,470 in 2008 (Lop Buri Provincial Office, 2010).

Lop Buri is considered a relatively wealthy province in Thailand (Felkner & Townsend, 2004). It ranked 19 out of 76 in GDP per capita (Lop Buri Provincial Office, 2010), with a GDP per capita in 2008 of 97,306 Baht—approx. US$2,800. The majority of the population is engaged in the agricultural sector. The major cash crops grown in Lop Buri are rice, sugarcane, cassava, maize, and sunflowers.

The climate is tropical, with seasonal temperatures ranging, on average, from 23.3ºC in December/January to 33.3ºC in April. Lop Buri has a monsoon climate. The rainy season, which is influenced by the Southeast monsoon, lasts from May to October. The average rainfall during May is approximately 170 mm, and peaks in September with approximately 280 mm. November through April is the dry season, a period in which the province is influenced by the Northeast monsoon (Thai Meteorological Department, 2008).

Elevation within the province ranges from 5-840 m above sea level, with the region divided into three major zones. First is floodplain between Chao Phraya River (approximately 20 kilometers west of the province) and Lop Buri River where the elevation is less than 20 m, with an average of 1% slope. This area is on the western section of the province, and is suitable for rice cultivation. Second is the alluvial plain that is couched between the Lop Buri River and Pa Sak River, with elevations that range from 20-100 m and an average slope of 1%. This area is mainly used for upland crops cultivation. Lastly, there are the mountain areas; with elevations of more than 100 m and an average slope of around 16%. The mountains are scattered throughout the province and cover roughly 30% of the landscape (Lop Buri Provincial Office, 2010; Oung-youang, 2000; Worakawin, 2003).

Lop Buri has protected forested areas, which include Sab Langka Wildlife Sanctuary in the far north of the province. Agricultural production, particularly cultivation of rice and upland crops such as maize, cassava, and sugarcane, is a dominant feature of Lop Buri's landscape. Water bodies include the Lop Buri River and Pa Sak River and reservoirs, e.g. Pa Sak Dam/Reservoir which was under construction in 1994 and completed in 1999.

Methods

Land-Cover Data

Land-cover data used in the study was based on the study by Patarasuk and Binford (2012). Land-cover classes were derived from Landsat images: 20 January 1989 (TM 4), 10 March 1998 (TM 5), and 8 March 2006 (ETM+). Initially, six land-cover classes including forest, water, plantation, rice, upland crops, and built-up areas were classified for each image. The overall land-cover classification accuracy for the 2006 image was 83%. Lastly, change trajectories method was used to classified areas that had forest loss and upland crops increase.

Logistic Regression Models

Logistic regression was chosen as a modeling technique given that the dependent variables in this study are binary – denoting the change or non-change of a land parcel (for example, conversion to upland crop production – 1 versus non-conversion to upland crop – 0). Logistic regression is a method that is commonly used to ascertain the importance of various independent variables and the degree to which they explain spatial variations of land-cover change (Mertens & Lambin, 2000). A backward stepwise likelihood-ratio method is used to estimate the logistic regression models. The backward stepwise procedure is preferred to forward stepwise as it reduces the risk of making Type II errors in the assessment of the significance of independent variable (Field, 2009).

This study relied on SPSS software (version 18) in the estimation of the logistic regression models. Positive values for parameter estimates indicate that the increasing values of the explanatory variable will increase the likelihood of the occurrence of the event, whereas negative values indicate that the larger values will decrease the occurrence of an event (Serneels & Lambin, 2001b). Wald χ^2 statistics and probability values were calculated to measure the predictive power and significance of independent variables. The confidence interval level used in the study is 95% (p-value < 0.05). Note that pseudo R^2 values were used to assess a model's goodness-of-fit; in particular, Nagelkerke R^2. Note that Nagelkerke R^2 is different from the classic R-square used in least-squares regression as the formula uses a log function (Nagelkerke, 1991). A pseudo R^2 of 0.2 is roughly equivalent to a classic R^2 of 0.5, and is considered as a value that would indicate a relatively good fit (Domencich & McFadden, 1975; Peterson, Bergen, Brown, Vashchuk, & Blam, 2009; Serneels & Lambin, 2001b). Lastly, it should be noted that the independent variables were standardized to zero mean and unit variance before running the logistic regression models to allow for unit-free comparisons (Braimoh & Onishi, 2007).

Dependent Variables

Four logistic regression models were developed in the study, reflecting the dominant land cover change trajectories between 1989-1998 and 1998-2006. These trajectories are defined as follows: (1) change to upland crops from 1989-1998 – Model 1; (2) change to upland crops from 1998-2006 – Model 2; (3) loss of forests from 1989-1998 – Model 3; and (4) loss of forests from 1998-2006 – Model 4. Land-cover trajectories were determined based on the findings in (Patarasuk & Binford, 2012), denoting periods that show the greatest differences between land covers. These trajectories were based on hybrid classification methods applied to LANDSAT images dated: 20 January 1989 (TM 4), 10 March 1998 (TM 5), and 8 March 2006 (ETM+). The distribution of land with trajectories analyzed with logistic regression models are shown in Figure 3-2. Binary values of dependent variables coded in SPSS are listed below:

Model 1: 1 trajectory change to upland crops from 1989-1998, 0 otherwise;

Model 2: 1 trajectory change to upland crops from 1998-2006, 0 otherwise;

Model 3: 1 trajectory change of forest loss from 1989-1998, 0 otherwise; and

Model 4: 1 trajectory change of forest loss from 1998-2006, 0 otherwise.

Independent Variables

Several spatially explicit independent variables were evaluated as potential determinants of land-cover conversion to upland crops and forest loss. A description of each independent variable is given below.

Elevation and Slope. Elevation data were derived from the ASTER Digital Elevation Model (DEM) 1°-by-1° tiles with 30 m x 30 m spatial resolution. The DEM was re-sampled to 28.5 m x 28.5 m to be consistent with the LANDSAT images. A slope gradient was calculated as percentage from the ASTER DEM using 3x3 cell neighborhood method.

Distance to forest edge. Distance to forest edge was calculated by using the Euclidean distance from “forest” pixels for 1989 and 1998 as derived from Patarasuk and Binford (2012).

Distance to Major towns within Lop Buri Province. Location of each District Administration Office was used for a point location for major towns. Lop Buri province consists of 11 districts and a total of 11 towns. Towns are used as a proxy for market locations, where farmers are known to sell their agricultural products. For simplification, distance to major towns in Lop Buri was performed based on a Euclidean distance algorithm.

Rainfall. Average annual rainfall for 1989-1998 and 1998-2006 were calculated from daily rainfall measurements from the major rainfall stations in Lop Buri and the neighboring provinces. The values were interpolated with using an inverse distance weighting (IDW) function .

Road network. Distance to roads was calculated based on Euclidean distance. The extent of road network was mapped six kilometers beyond the province’s boundary line to reduce edge effects. Road density was expressed by km/km^2 and was also calculated using a buffer that extended six kilometers beyond the province boundary line. Distance to roads and road density were calculated for three dates: 1989, 1998, and 2006. Changes in the distance to roads and road density between 1989-1998 and 1998-2006 were also calculated.

Population. Population data were obtained from the Community Development Department (CDD) in Thailand, which conducts surveys every 1-2 years. Population data were compiled at tambon level (equivalent to communes) for 1989, 1998, and 2006. Population density (persons/ km^2) was calculated for each tambon as well and changes in population density for the 1989-1998 and 1998-2006 time periods (Figures 3-3 and 3-4). An additional dichotomous independent was created to denote tambons with a population density that was above the median (to differentiate them from tambons at or below the median population density). This variable was included to test if highly populated areas affected land-cover change in a way that would suggest they were affiliated with a different statistical population (Figure 3-5). Subsequently, this variable was used as an interactive variable, multiplied with other independent variables such as slope, distance to towns, and distance to roads.

All independent variables were pre-tested for potential multi-collinearity using Pearson's product moment correlation. Independent variables selected to perform logistic regression models had a Pearson's correlation of less than or equal to 0.8. Variables with correlations above 0.80 are considered to be highly correlated and redundant in terms of their explanatory power (Field, 2009; Menard, 2002). Hence, variables were screened and chosen to reduce the likelihood of complications arising from multi-collinear relations amongst regressors (inefficiencies arising from inflated standard errors).

Sample Selection

Data from a stratified random sample were generated for each logistic regression model. The total sampling points for each model was N = 50,000. These sampling points were divided equally between pixel values of 0 and 1 – denoting pixels with no land cover change (Y = 0) and those where a land cover change was observed (Y = 1); thereby, yielding a stratified sample of 25,000 points for each case. A random sampling method was preferred as it helped to reduce spatial autocorrelation and minimize the size of the dataset (Braimoh & Vlek, 2005; Peterson, et al., 2009).

Results and Discussion

The results of the correlation analysis reveal that elevation and slope are highly correlated. To sidestep the possibility of collinearity, elevation was omitted as an independent variable in all of the models. Note that in Lop Buri province, elevation did not appear to play a role in land-cover change as upland crops were grown at relatively higher elevations compared to lower elevation where rice paddies were mostly found (Patarasuk & Binford, 2012). Next, distance to roads for the two consecutive dates were also determined to be highly collinear; thus, distance to road for later date was omitted from the list of independent variables. Hence, distance to roads in 1998 was omitted in 1989-1998 models (i.e., Models 1 and 3) and distance to roads in 2006 was dropped in 1998-2006 models (i.e., Models 2 and 4) Road density and population density also posed the same collinearity problem. Thus, the same logic was applied to road density and population density. Road density and population density for 1998 were dropped from the list of viable independent variables in Models 1 and 3; and road density and population density for 2006 were dropped in Models 2 and 4.

Logistic Regression Analysis

The results of the four logistic regression models are shown in Tables 3-1 through 3-4. Only variables that tested significant at the 95% confidence level were retained in the models. Positive coefficient values ($\beta > 0$) indicate that the higher the value of an independent variable, the greater the probability of observing a land-cover change. In contrast, negative coefficient values ($\beta < 0$) indicate that the higher value of an independent variable, the smaller the probability of observing a land-cover change. Note that "exp (β)" represents the standardized odds ratio, and measures the likelihood of observing the trajectory if the independent variable is increased by one standard deviation (Braimoh & Vlek, 2005; Serneels & Lambin, 2001b). Table 3-5 compares the signs and differences of estimated coefficient for selected independent variables. Lastly, the Wald (Chi-square) statistics indicates relative importance or weight associated with each independent variables in a model (Mertens & Lambin, 2000). The larger the Wald statistic, the greater the impact or significance of the variable in question.

Change to Upland Crops Models (Models 1 And 2)

The results of the logistic models for the change to upland crop are shown in Tables 3-1 and 3-2. Both models produce satisfactory outcomes in terms of goodness-of-fit outcome, with Nagelkerke's R-Square values of 0.312 and 0.467, respectively for the first- and second-time periods examined.

The results suggest that biophysical properties (such as slopes, rainfall, distance to towns, and distance to forest edge) play an important role in the land conversion process. The results suggest that, among these biophysical variables, "distance to forest edge" and "slope" are among the most influential factors. The negative coefficients associated with distance to forest edge indicates that there is an increase (decrease) in the likelihood of conversion to upland crops as the distance to forest edge declines (increases). This is consistent across both time periods. Slope is also shown to have a negative relationship with upland crops cultivation. As slope increases (i.e., as land becomes steeper), upland crops cultivation is less likely to occur. Likewise, as the distance to towns increases (1989-1998), so does the likelihood of upland crops cultivation. The results suggest that land conversion to upland crops occurs around edges of forests and settlements, with upland crop fields converted at the expense of forests. Note that as distance to towns increase for the period 1998-2006, so does the likelihood of upland conversion, as the estimated coefficient for this variable is positive for the period 1998-2006. This seemingly conflicting result suggests that upland crops cultivation over the period 1989-1998 occurs near towns, yet occurs at a greater distance away from towns for the period 1998-2006. The result suggests that competition for land around existing and expanding settlements forces people to cultivate upland crops elsewhere in the region (Entwisle, Walsh, Rindfuss, & VanWey, 2005).

Rainfall is a variable which also has different outcomes for the two time periods examined. It is a significant and negatively related factor for 1989-1998, but shown not to be significant for 1998-2006. In short, lower average rainfall totals are associated with higher levels of upland crop conversion during the earlier period; whereas rainfall is not statistically relevant in the later period. This suggests that upland crop conversion may have come at the expense of rice paddies from 1989-1998. Basically, farmers in Lop Buri opted to turn rice paddies to upland crop fields because upland crops are more tolerant to droughty conditions when compared to rice, which requires more water to grow (Devendra & Thomas; Oung-youang, 2000).

Distance to roads also plays a marked role in explaining the change to upland crops. Distance to roads is significant in the model as both a stand-alone and interactive variable; with coefficient values that reveal several interesting associations. For the period 1989-1998, distance to roads has a positive relationship with upland crop cultivation; and a negative relationship for 1998-2006. Positive relationship implies that as distance to roads increases, upland crop cultivation increases. In contrast, negative relationship implies that as distance to road increases, upland crops cultivation decreases. Yet the signs of these coefficients cannot be interpreted without considering the signs associated with the interactions with other variables such as distance to towns or for land parcels associated with populations that are above the median value (both of which are associated with negative coefficients). Hence, there is a predominant and implied interaction effect, from the numerous estimated negative coefficients associated interaction terms which involve “distance to roads”. The results suggest that as the distance to roads increases for land that surrounds highly populated areas, there is an increase in land conversion to upland crops. The results are likely to have been influenced by changes in the road network which are either due to network development or road removal due to the Pa Sak Dam/Reservoir construction which directly affected upland crop areas. The negative coefficient associated with road density indicates that upland crop conversion may be taking place at locations that are relatively peripheral to settlements, in land that may be accessible by way of only a few roads. The significance of numerous interaction terms involving distance to roads and road density suggests that the relationship between land conversion and accessibility to land via the road network is complex. The results of the logistic models also highlight the relevance of the interaction between distance to roads and distance to towns as a factor that explain upland crop conversion. The results show negative relationships for both time periods. This indicates that areas that are both farther from roads and towns are less likely to be converted to upland crops. This suggests that the conversion of inaccessible land requires an increase in transportation costs for shipping upland crop products to market areas that are farther away. Hence, the remoteness of land lowers the likelihood of conversion. These results also correspond with other studies in which distance and limited accessibility are a barrier for landscape conversion (Nagendra, Southworth, & Tucker, 2003; Rojnkureesatien, 2006). All in all, complexities notwithstanding, there is statistical evidence that roads give accessibility to land and encourage a conversion of the landscape (Chomitz & Gray, 1996; Nelson & Hellerstein, 1997).

Population pressure variables are also found to be important factors in accounting for the likelihood of upland crop conversion. Both initial population density and population density change are shown to be negatively associated with upland crops cultivation in both time periods. This suggests that the lower the initial densities or the lower the density change, all other things being equal, the more likely one is to encounter upland crops cultivation. This result implies that land-cover change to upland crop cultivation is associated with a more rural-agrarian population where density is low, and more land is available for conversion.

The study further assessed how population pressures affect land-cover change by using interaction terms which involve several population-road variable combinations.

Tambons which have population densities that are above the median were chosen to interact with other variables in the model to see if highly populated tambons constitute a separate and distinct statistical population. In both periods, there is evidence that highly populated tambons are unique in terms of their propensity for land conversion. Lop Buri province consists of 121 tambons, 61 (60) of which had populations above the median population in 1989 (1998). The results show that within the highly populated tambons, the slope of the land is less likely to prevent people from converting land to upland crops than it is throughout the remainder of the study area. In addition, distance to towns was shown to be less of a conversion deterrent in and around highly populated tambons from 1989-1998. Thus, areas that are adjacent to highly populated settlements are more likely to place pressure on the landscape to convert the land to upland crop fields. Note also that there is evidence that larger and rapidly growing tambons, from the subset of tambons that are above the median population size, are more likely to encourage upland crop conversion. The increased likelihood of land conversion to upland crop cultivation in or near highly populated or rapidly growing tambons may be viewed as a phenomenon that is partly a risk avoidance strategy employed to take advantage of upland crop tolerance in light of climate change and increased variability and partly an attempt to maximizing access (and minimizing transport costs) to markets where upland crops are sold.

Overall, the results here suggest that upland crop conversion is most likely associated with tambons that are either (a) rural-agrarian and slower growing, with low population densities and relatively high access to markets, or (b) tambons that are above the median population, rapidly growing, and near markets. Differences in the statistical significance of variables and the reversal of signs of some estimated coefficients between the two periods examined is evidence that the drivers and their impact on the conversion process are changing over time. This is no surprise as once land is converted to the production of upland crops, it is no longer available for conversion in the subsequent time period. This would explain anomalies such as reversal of the sign associated with various interaction variables or the inclusion of new variables in the model for period two. As conditions change and competition for land becomes part of the emergent dynamic between urban and agricultural land uses (in light of changing road densities, changing populations, conversions, etc.), the coefficients that embody and define the complex relationships between the likelihood of conversion and the drivers that influence conversion should also be expected to change. This implies that one should gain a deeper understand of the preconditions that exist in a setting, before attempting to interpret a model or its estimated coefficients. Nevertheless, the results of the upland crop conversion model highlights the need to further examine the properties of road networks and their ability to affect the remoteness or accessibility of land in relation to the spatial organization of settlements and the demand for agricultural products which, in turn, affect competition among land uses and the process of land conversion.

Forest Loss Models (Models 3 and 4)

The results of the logistic models of forest loss are shown in Table 3-3 and Table 3-4 for models 3 and 4, respectively. Forest loss models for both time periods provide an excellent fit when compared to the upland crops models. Note that Nagelkerke's R-Square for the period 1989-1998 is 0.761 and is 0.772 for 1998-2006. As in the case of the upland crop models, biophysical variables are found to be the most important in terms of predicting forest loss. In particular, “distance to forest edge” and “slope” are the most significant factors that influence forest loss. Slope, distance to towns, and distance to forest edge all have a negative relationship with forest clearing for both time periods. In other words, the likelihood of forest loss increases as slope, distance to towns, or distance to the forest edge decreases. Note that rainfall shows a positive relationship with forest loss for the first time period, yet is not an explanatory factor in the second time period.

The negative coefficient of slope suggests that as the landscape becomes steeper, forest clearing decreases. This indicates that steep slopes prevent forest loss; and is consistent with the argument that slopes acts as a natural barrier for forest protection (Cropper, et al., 2001b). Distance to towns and distance to forest edge have negative coefficients, which suggests that forests are more likely to be cleared in areas that are proximate to towns and distant from remote forested areas. Between 1989-1998 forest loss occurred heavily on the northwest section of the province. However, forest clearing has shifted towards the western section of the province between 1998-2006. Deforested areas are also located on the southern part of Sab Langka Wildlife Reserves and Pa Sak Dam/Reservoir, where forests were cleared for dam construction (Figure 3-2).

Road networks were also shown to play a role in explaining the likelihood of forest loss. Roads are more important in the period 1989-1998 than for 1998-2006. Distance to roads for the first time period is positively related to forest loss, indicating that as distance to roads increases, forest loss increases. This result is in direct conflict with the many studies that show that as distance to roads decreases (increases), forest clearing increases (decreases) (see Wyman & Stein, 2010; Braimoh and Onishi, 2007; and Laurance, et al., 2002). This may suggest that forested areas were being cleared faster than the road network was being constructed. The finding that forest loss is occurring at greater distances from roads might also be a byproduct of the lack of deforestation in areas contiguous to those already deforested. In short, deforestation may be taking place in areas were road density is low, and in areas that are on the fringe of new roads or in remote areas that are more distance to existing roads. This is supported by the estimated negative relationship between forest loss and road density, and may be a signal that the process of deforestation may be advancing faster than the expansion of the road network. This pattern suggest that there might be illegal logging activities going on in Lop Buri, though not many documents has specially documented in Lop Buri province, but this is the trend in other part of Thailand as well (Kontogeorgopoulos, 2009; Kummer & Turner, 1994). Note that changes to road network in terms of distance to roads and road density plays a more important role in the 1998-2006 period than it did from 1989-1998. Distance to road change was positively associated with forest loss, and can be linked to road removal activities associated with the Pa Sak Dam project; which accelerated forest clearing. In short, road removal caused road density to decrease, and contributed greatly to an increase in forest loss.

Population pressures were also shown to be contributors of the forest loss process. Population density and changes in population density are also shown to be explanatory factors responsible for advancing forest loss. Note that for the period 1998-2006, forest loss occurred more rapidly in areas with slower growing population densities; as indicated by the estimated negative coefficient.

Similarly to the upland crop models, there are higher degrees of forest loss in tambons with populations and/or population densities that are above the median. The results show that, for both time periods, the loss of forest cover is less apt to be prevented by steep slopes in areas with above median populations; as suggested by estimated coefficients associated with the interaction variables. Overall, as the percentage of slopes increases, the likelihood of forest clearing decreases; yet the decline is less in highly populated areas. This suggests that the people have cleared forests in lower slopes prior to 1989, thus the land available for upland crop productions are limited so people have to move up to higher slopes to clear forested areas as settlements and the demand for upland crops expand. The results of the forest loss models are consistent with upland crop models in which most of these forested areas in Lop Buri Province are replaced by upland crops, particularly, between 1989-1998 (Figure 3-2). Moreover, forest loss is still found at distances that are relatively closer to towns within areas where population density is higher than the median.

In sum, the four models suggest that the predominant drivers of upland crop conversion and forest loss are slope, distance to forest edge, distance to towns as it interacts with distance to roads, and population (specifically highly populated or population-dense areas). These variables, and interactive combinations thereof, are the most consistent predictors across the four models, with coefficient signs that are relatively stable across the models and years. Other variables such as distance to roads and rainfall show different results depending on the type of change and the time period. Lastly, closer inspection of interaction variables may be warranted to uncover nuances in the statistical relationships that result from the presence of possible multiple statistical populations within the study region. This study established that coefficients associated with areas that were above the median population were significantly different from other areas, as the interactions between population size and numerous biophysical variables were shown to be non-random. Qualitative information and the use of dummy variables may prove useful in discovering other relationships that could further our understanding of the complex nature of land cover change as part of the human-environment interaction.

This research has shown the importance of various drivers of land-cover change as they pertain to upland crops production and forest loss. The study examined biophysical and demographic factors rather than socio-economic factors (such as market conditions, production costs, and product prices) to determine the predominant drivers of land-cover change. Socio-economic factors could also be incorporated to capture the linkages between these drivers and land-cover change as they pertain to other features of the human-environment interaction. As Geist & Lambin (2002) stated, land-cover change is a combination of several drivers both biophysical and socio-economic. Suggested socio-economic variables are such as agricultural product prices (Cropper, et al., 1999), timber price (Cropper, et al., 1999), education (Pichon, 1997), and types of land tenure (Chomitz & Gray, 1996). Furthermore, other biophysical properties such as soil types and soil attributes (Chomitz & Gray, 1996; Serneels & Lambin, 2001b) could be incorporated in these models as well. Another recommendation is to capture the more refined characteristics of the road network as it pertains to connectivity, accessibility, road type, flow and spatial interaction potential, and traffic volume. Major highways usually connect major towns within and outside the province where as local roads connect villages and farmlands. Thus, different types of roads could be separated out as distinct variables in the logistic regression model (e.g. major roads vs. minor roads) instead of classifying all roads in a similar fashion. Lastly, the use of additional interaction terms and qualitative (dummy) variables might prove useful in testing to see if there are multiple statistical populations other than just areas which are above the median population. Model expansion might be warranted to capture the more detailed aspects of the drivers of land-cover change. The above mentioned variables were not used because due to a limited data availability and it is beyond the scope of the study.

Most spatially explicit models of land-cover change have focused on forest loss (deforestation). A full set of integrated models could be developed to investigate how changes in one land cover type affect other land cover types and this sets the basis of the future research. Ultimately, these types of modeling efforts can lead to a better understanding of the dynamics and inter-relationships between upland crop conversion and forest loss, and the degree to which spatially variable population pressures and characteristic of the road network contribute to land cover change.

Conclusions

This study integrates the use of GIS, remote sensing and spatially explicit data to develop four logistic regression models of upland crop expansion and forest loss during the periods of 1989-1998 and 1998-2006. The relationships between these models and driving forces of these land-cover changes were quantified and explained. Biophysical properties, which include slopes and distance to forest edge, and distance to towns have the most influence in these two types of land-cover changes in Lop Buri Province. Furthermore, various characteristics of the road network such as distance to roads and road density are also shown to be influential, with results that are explained by the context under which the land use changes occurred. Lastly, population pressure is also shown to be a contributing factor to upland crop conversion or forest loss. This is especially true for especially high populated areas were the competition for land resources is most intense.

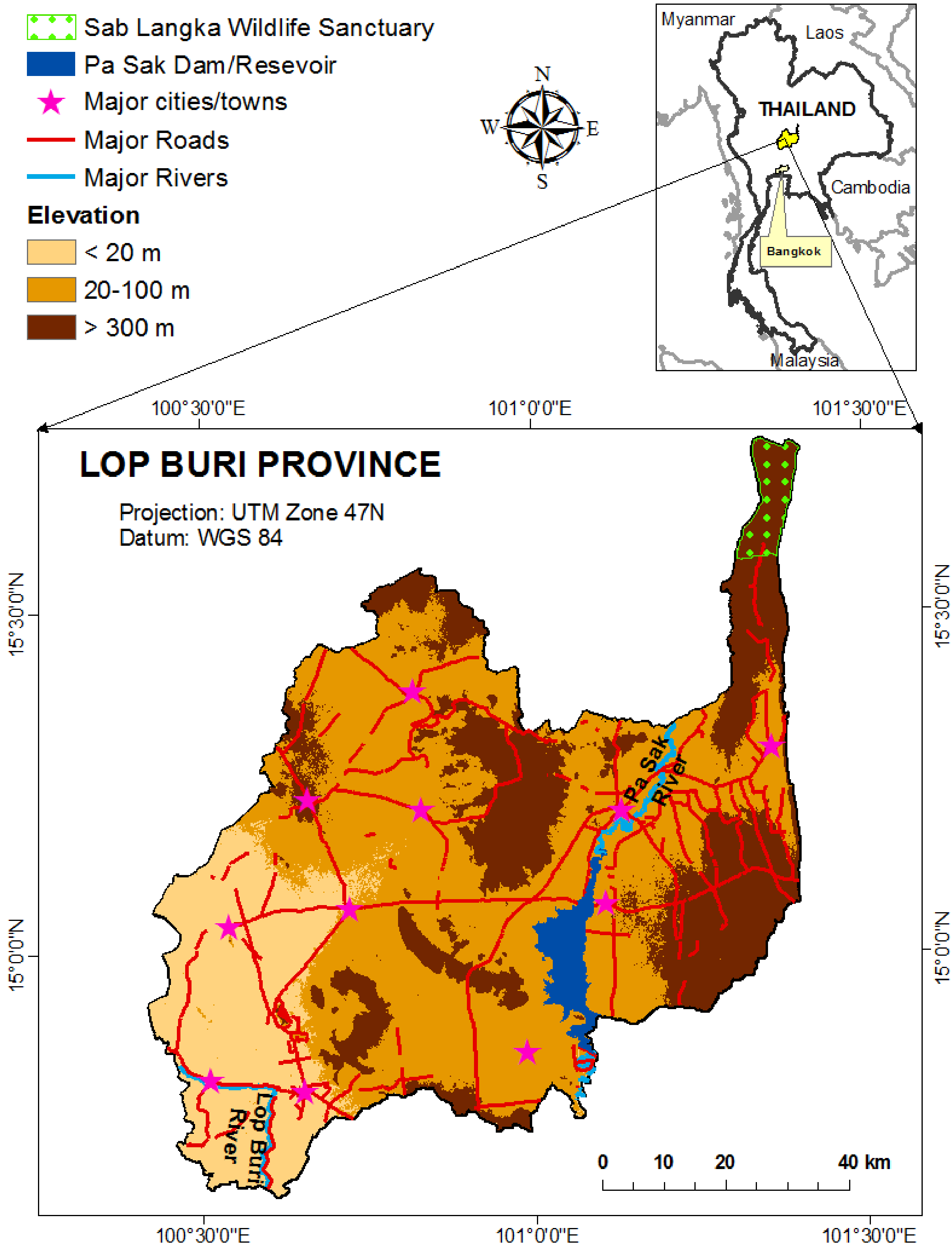


Figure 3-1. The study area, Lop Buri province, Thailand.

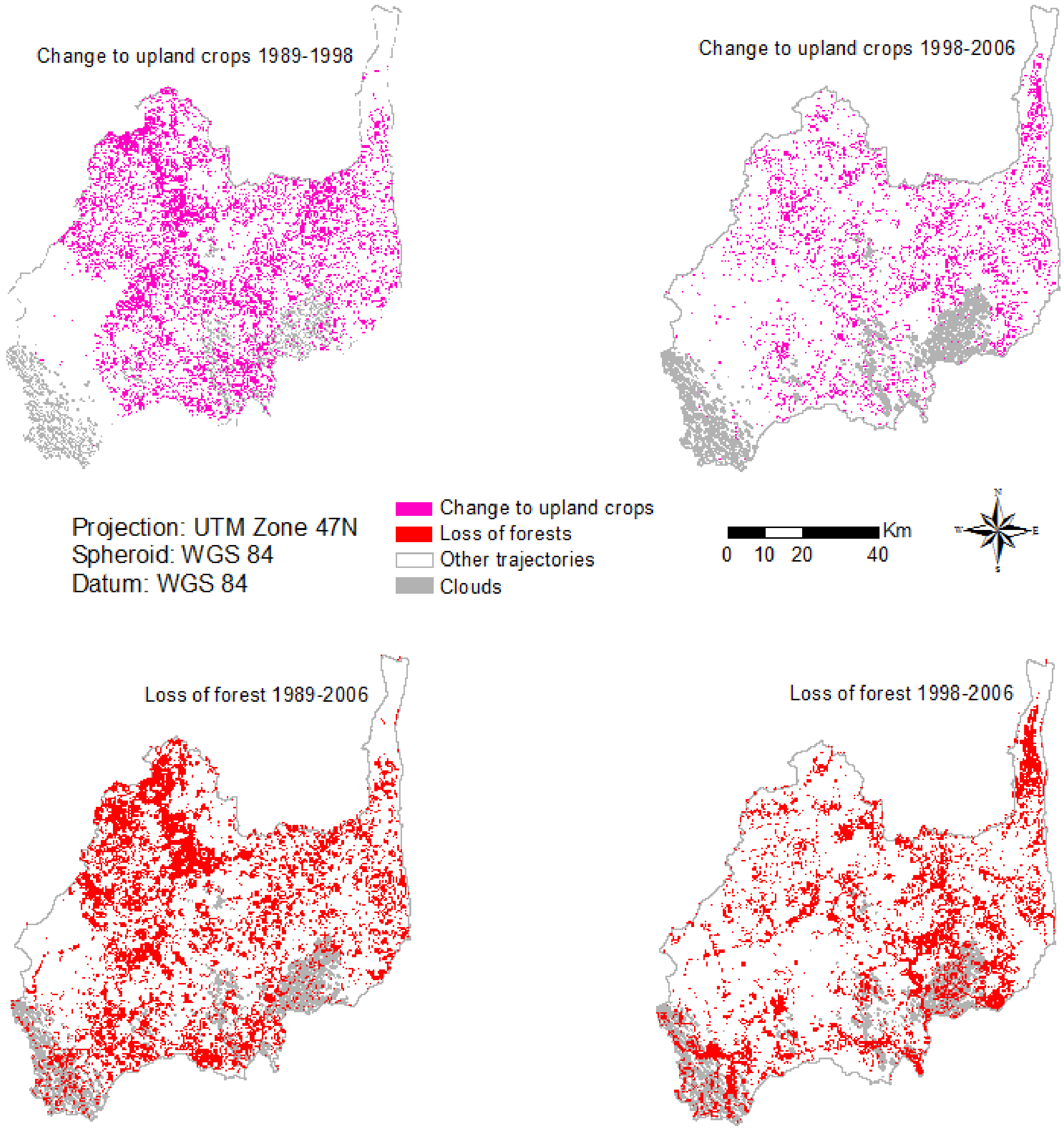


Figure 3-2. Areas that have changed to upland crops and loss of forests.

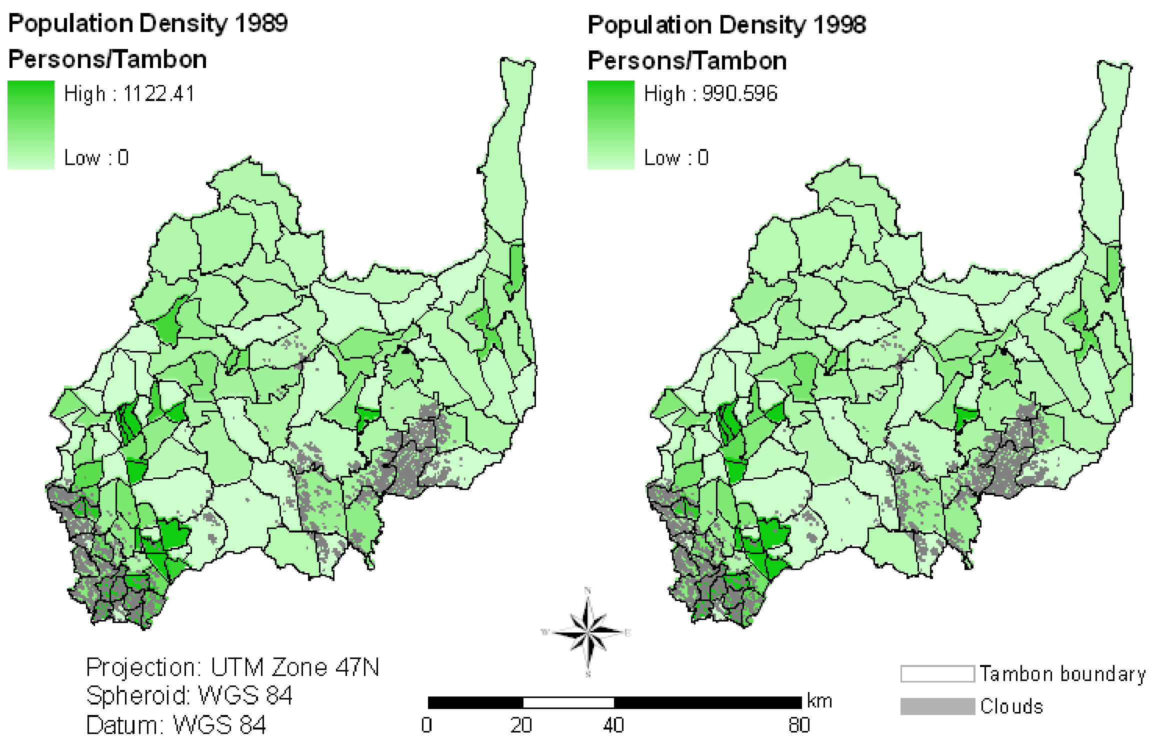


Figure 3-3. Population Density by Tambon.

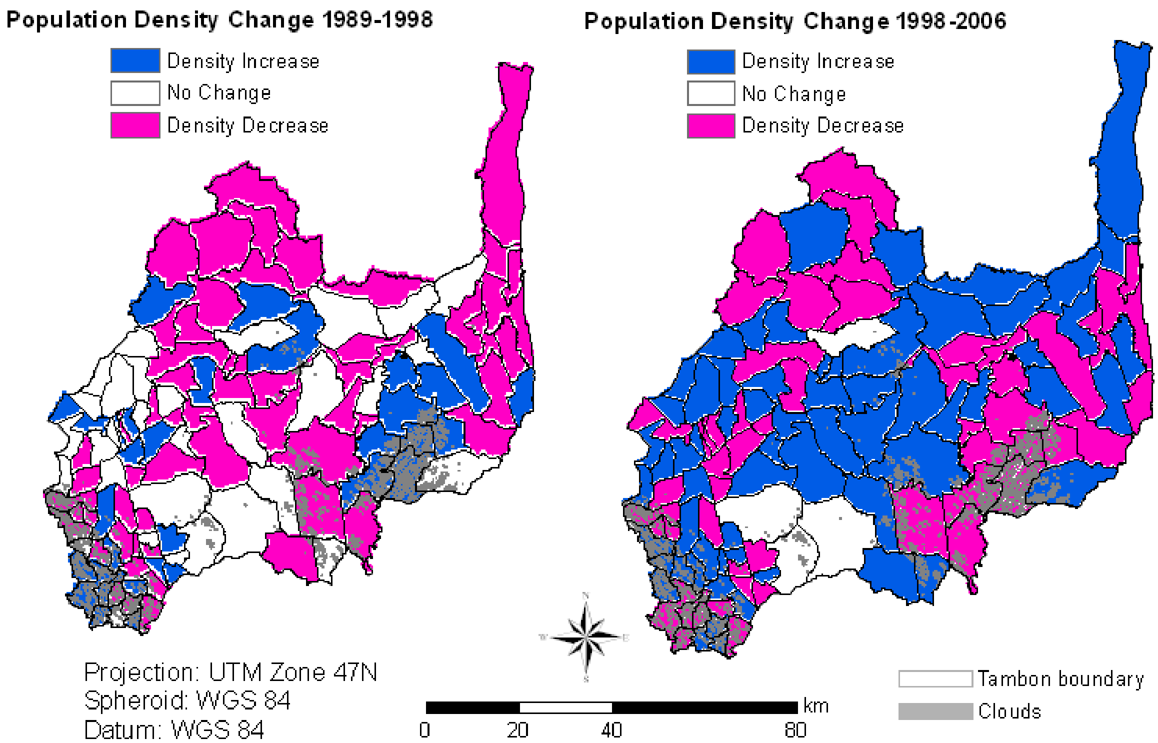


Figure 3-4. Population change

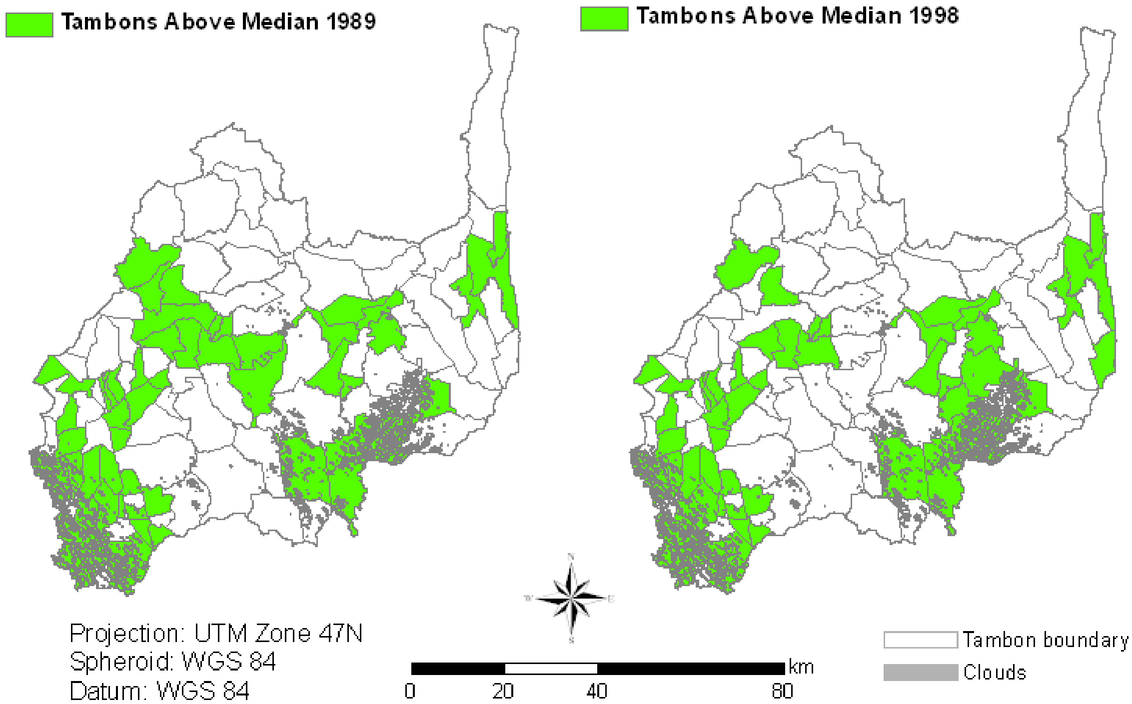


Figure 3-5. Population Density above median by Tambon

Table 3-1. Model 1: Logistic regression output for change to upland crops 1989-1998 model.

Independent Variables	β	S.E.	Wald	Sig.	Exp(β)
Single Variables:					
Slope	-.744	.018	1632.643	<.000	.475
Distance to towns	-.337	.015	530.756	<.000	.714
Distance to forest edge	-1.280	.019	4456.341	<.000	.278
Distance to roads	.082	.015	28.798	<.000	1.085
Road density	-.104	.015	50.618	<.000	.901
Initial population density	-.239	.049	23.896	<.000	.787
Population density change	-.459	.045	105.000	<.000	.632
Rainfall	-.478	.013	1460.746	<.000	.620
Interaction Variables:					
Distance to roads * distance to town	-.152	.013	129.299	<.000	.859
Population Above Median * slope	.357	.035	104.659	<.000	1.429
Population Above Median * Distance to towns	.203	.034	35.456	<.000	1.226
Population Above Median * Distance to roads	-.491	.052	87.927	<.000	.612
Population Above Median * Road density	.129	.033	15.129	<.000	1.138
Population Above Median * Distance to road change	-.369	.035	108.029	<.000	.692
Population Above Median * Road density change	-.201	.026	61.862	<.000	.818
Population Above Median * Initial population density	-.400	.067	35.970	<.000	.670
Population Above Median * Population Density Change	.343	.048	49.995	<.000	1.409

Nagelkerke R Square = 0.312
-2 Log Likelihood = 55082.829
Chi-Square = 609.161; Sig. < 0.0001

Table 3-2. Model 2: Logistic regression output for change to upland crops 1998-2006 model

Independent Variables	β	S.E.	Wald	Sig.	Exp(β)
Single Variables:					
Slope	-1.381	.027	2578.371	<.000	.251
Distance to towns	.081	.016	25.168	<.000	1.085
Distance to forest edge	-2.330	.030	5913.064	<.000	.097
Distance to roads	-.131	.017	60.422	<.000	.877
Distance to road change	-.126	.016	59.834	<.000	.882
Road Density change	-.047	.012	14.512	<.000	.954
Initial population density	-.322	.064	25.521	<.000	.725
Population density change	-.562	.028	413.701	<.000	.570
Interaction Variables:					
Distance to roads * distance to town	-.083	.009	79.036	<.000	.921
Population Above Median * slope	.771	.046	278.365	<.000	2.162
Population Above Median * Distance to towns	-.199	.035	32.558	<.000	.819
Population Above Median * Distance to Forest edge	.194	.053	13.189	<.000	1.214
Population Above Median * Distance to roads	-.407	.049	67.885	<.000	.666
Population Above Median * Road density	-.122	.027	20.686	<.000	.885
Population Above Median * Distance to road change	-.348	.038	84.674	<.000	.706
Population Above Median * Road density change	-1.151	.086	179.983	<.000	.316
Population Above Median * Initial population density	-.329	.050	44.132	<.000	.719
Population Above Median * Adjacent to tambons that have population above median	-1.075	.446	5.815	.016	.341

Nagelkerke R Square = 0.467
-2 Log Likelihood = 46449.426
Chi-Square = 1959.705; Sig. = 0.000

Table 3-3. Model 3: Logistic regression output for forest loss 1989-1998 model

Independent Variables	β	S.E.	Wald	Sig.	Exp(β)
Single Variables:					
Slope	-1.482	.026	3312.922	<.000	.227
Distance to towns	-.581	.022	718.040	<.000	.559
Distance to forest edge	-6.336	.057	12402.814	<.000	.002
Distance to roads	.186	.028	43.889	<.000	1.204
Road density	-.062	.024	6.612	.010	.940
Distance to road change	-.073	.026	7.642	.006	.929
Rainfall	.072	.018	15.760	<.000	1.075
Interaction Variables:					
Distance to roads * distance to town	-.321	.020	252.257	<.000	.725
Population Above Median * slope	.570	.041	194.019	<.000	1.768
Population Above Median * Distance to towns	1.375	.048	821.578	<.000	3.956
Population Above Median * Road density	.210	.035	36.437	<.000	1.233
Population Above Median * Distance to road change	.119	.043	7.625	.006	1.126
Population Above Median * Initial population density	-.381	.019	405.467	<.000	.683
Population Above Median * Population Density Change	.039	.012	9.702	.002	1.040
Population Above Median * Adjacent to tambons that have population above median	-2.071	.652	10.081	.001	.126

Nagelkerke R Square = 0.761
-2 Log Likelihood = 25896.442
Chi-Square = 7986.328; Sig. = 0.000

Table 3-4. Model 4: Logistic regression output for forest loss 1998-2006 model

Independent Variables	β	S.E.	Wald	Sig.	Exp(β)
Single Variables:					
Slope	-1.655	.028	3594.653	<.000	.191
Distance to towns	-.374	.023	259.181	<.000	.688
Distance to forest edge	-6.000	.056	11665.007	<.000	.002
Distance to road change	.171	.020	76.483	<.000	1.186
Road Density change	-.069	.021	10.402	.001	.933
Population density change	-.812	.028	820.526	<.000	.444
Interaction Variables:					
Distance to roads * distance to town	-.203	.014	217.039	<.000	.817
Population Above Median * slope	.765	.044	306.045	<.000	2.148
Population Above Median * Distance to towns	1.505	.050	889.343	<.000	4.505
Population Above Median * Distance to roads	-.199	.049	16.719	<.000	.820
Population Above Median * Road density	.227	.033	47.532	<.000	1.255
Population Above Median * Distance to road change	.245	.034	53.212	<.000	1.278
Population Above Median * Initial population density	-.080	.027	8.701	.003	.923
Population Above Median * Population Density Change	1.032	.044	544.536	<.000	2.805
Population Above Median * Adjacent to tambons that have population above median	-1.109	.396	7.838	.005	.330

Nagelkerke R Square = 0.772
-2 Log Likelihood = 24848.671
Chi-Square = 7396.390; Sig. = 0.000

Table 3-5. Sign of the coefficient (β) comparison across four models.

Independent Variables	Model 1 (change to upland crops from 1989-1998)	Model 2 (change to upland crops from 1998-2006)	Model 3 (loss of forest 1989-1998)	Model 4 (loss of forest 1998-2006)
Slope	-	-	-	-
Distance to towns	-	+	-	-
Distance to forest edge	-	-	-	-
Distance to roads	+	-	+	
Road density	-		-	
Distance to road change		-	-	+
Road Density change		-		-
Initial population density	-	-		
Population density change	-	-		-
Rainfall	-		+	
Distance to roads * distance to town	-	-	-	-
Population Above Median * slope	+	+	+	+
Population Above Median * Distance to towns	+	-	+	+
Population Above Median * Distance to Forest edge		+		
Population Above Median * Distance to roads	-	-		-
Population Above Median * Road density	+	-	+	+
Population Above Median * Distance to road change	-	-	+	
Population Above Median * Road density change	-			+
Population Above Median * Initial population density	-	-	-	-
Population Above Median * Population Density Change	+	-	+	+
Population Above Median * Adjacent to tambons that have population above median		-	-	-

CHAPTER 4
ROAD NETWORK CONNECTIVITY AND LAND-COVER DYNAMICS IN LOP BURI PROVINCE

Roads are viewed as a means of social and economic development because they link regions, places, people and economies together. Improvement of the road network increases accessibility and mobility while reducing distance to destinations, travel costs and travel time. Development of road networks has been proven to help social development and economic prosperity (Buurman & Rietveld, 1999; Deichmann, Kaiser, Lall, & Shalizi, 2005; Gutierrez & Urbano, 1996). Some social and economic development associated with road network improvements include better access to education (Bourdet, 1998), better health care delivery (Airey, 1992), greater employment opportunities (Windle & Cramb, 1997), increased household income (Jacoby, 2000), and reductions in poverty (Fan & Chan-Kang, 2005). Moreover, road development may also enhance an area's economic development by providing basic infrastructure for investment and the harnessing of local and regional economic development potential (Bourdet, 1998; Lampe, 1983).

Despite these many social and economic benefits, roads are also perceived as cultural artifacts that lead to land-cover change, which may contribute to adverse environmental effects at all scales from local to global (Coffin, 2007; Forman & Alexander, 1998). The changes result from the accessibility that roads provide, not roads *per se* (Stone, et al., 1991), and accessibility is a primary mechanism for efficient delivery of humans to their destinations such as forests, agricultural land, or market towns (Forman, 1998; Forman, et al., 2003; Saunders, Mislivets, Chen, & Cleland, 2002).

The environmental effects of access to forested areas have been studied largely in tropical rainforests, such as in the Amazon region. An extensive road development in this region, especially in the Central Rondônia state of Brazil, which led to the 'fishbone' structure of road network pattern, resulted in 35% of the area deforested between 1985 and 1995**.** The forested areas were largely replaced by crop farms, pastures and human settlements (Alves, et al., 1999). Furthermore, better accessibility to agricultural land or markets can encourage people to convert lands (Munroe, Southworth, & Tucker, 2004). Extension of the network or road improvements (e.g. from unpaved to paved) allow farmers to reduce travel times and transportation costs to market towns (Dorosh, Wang, You, & Schmidt, 2009; Verburg, Overmars, & Witte, 2004) by permitting better vehicular access to agricultural and markets during all seasons (Verburg, et al., 2004). Thus, farmers tend to increase agricultural productivity by expanding crop production along developed roads, which ultimately results in land-cover conversion (Dorosh, et al., 2009; Hafner, 1970; Soares-Filho, et al., 2004).

Land-cover conversion has been a major global environmental concern as it influences the functioning of the Earth's natural systems as well as human-environmental relationships (Global Land Project, 2005; Kummer & Turner, 1994; Lambin, et al., 2001). Examples of effects upon global environmental systems include, but are by no means limited to, habitat loss (Brooks, et al., 2002) and alteration of local and regional climates (Dale, 1997). Therefore, road network development is a challenging problem as its presence shows a strong positive correlation with economic and national wealth, but is simultaneously linked to ecological disturbance and natural resource degradation (Wilkie, et al., 2000).

Several researchers have studied linkages between road network connectivity and land-cover dynamics by using various road network indices as a measure of road connectivity. Higher road connectivity implies greater accessibility to destinations such as farmland and markets**.** Coffin (2009), ShiLiang et al. (2007), and Rojnkureesatien (2006) used concepts based on graph theory to study network connectivity. Graph theory is a mathematical construct used to simplify the essential characteristics of real-world network connectivity, through the representation of edges (i.e., road segments) and nodes (i.e., road intersections) (Balakrishnan & Ranganathan, 2000; Harvey & Shih-Lung, 2001; Rodrigue, et al., 2009). Graph theory based methods are useful because they provide a topology describing the structure of a transportation network (Kansky, 1963). Coffin (2009) used 23 different network indices to investigate relationships between road network development and land-cover dynamics in the Santa Fe River watershed of North Central Florida. The author found that increased numbers of roads do not necessary improve the network connectivity because many roads were developed as dead-ends instead of linking one road to another. Moreover, the author noted that the increase in the amount of roads in the study area contribute to land-cover change, particularly from agricultural to urban landscape. Similarly, Rojnkureesatien (2006) carried out a study of road network indices and forest cover dynamics in Nang Rong district, Thailand. Rojnkureesatien found that increase in amount of road increases network indices. Most of these newly developed roads are linked to existing roads; thus, creating better connectivity. This increase had an association with forest cover decline because increased network connectivity increased accessibility to forests.

Hence, these authors found a pattern of land-cover change relating to road network development.

Road networks in Thailand have been built and developed to serve several purposes including the support of military movement, enhancing relationships between neighboring countries (e.g. Thai-Laos Friendship), and enhancing regional and local social and economic development. The First National Economic and Social Development Plan (National Plan) of 1961 and other subsequence National Plans have extensively developed road networks in Thailand (Rojnkureesatien, 2006). One of the National Plan's strategies is to facilitate moving commercial crops from remote areas both to market areas and to major cities for distribution to foreign markets (Rojnkureesatien, 2006; Torres, Hubert, & Franck, 2004).

The provincial economy of Lop Buri is largely agrarian requiring commercial crops to be transported from farms to markets. The original road network was initiated by General Por Piboonsongkram during the 1930s to support military activities thereby turning the province into a military-based province (Office of Information and Technology: Thepsatri Rajabhat University, 2008). In more recent decades, roads have been built to improve the quality of life and to enhance economic activities in conjunction with the various National Plans (Puri, 2006; Rojnkureesatien, 2006).

The main purpose of this study is to investigate the relationships between the development of the road network in Lop Buri province and land-cover dynamics between 1989 and 2006. The research questions are: 1) How has road connectivity changed as the roads network was developed?, 2) How has any changing road connectivity been associated with changing of land cover?, and 3) What is the distribution of land cover before and after road network development?

For this particular study, road network development refers to road network extension, and the terms are used interchangeably throughout the paper. Fifty-six intensive study areas (ISAs) were chosen to compare areas that had undergone network development at different time periods. Graph theory-based approaches measure the levels of road connectivity before and after network development. Moreover, Kendall's Tau, Kolmogorov-Smirnov and Wilcoxon tests are employed to seek any significant relationships between road network development and land-cover dynamic. The major hypotheses are as follows: 1) As road network in Lop Buri province extended, network connectivity increased, 2) Higher road connectivity has been association with declines in forested area, and an increase in both agricultural area (including rice and upland crops) and built-up areas, and 3) There is a statistically significant decrease in the amount of forest cover as well as increase in agricultural areas and built-up areas after road network development.

Study Area

Lop Buri province lies in the Central Region of Thailand (Figure 4-1), approximately 150 km from the capital Bangkok. It is situated between latitudes 14º39′ and 15º35′N and longitudes 100º24′ and 101º26′E, encompassing a total area of approximately 6,300 km^2 and with a human population of 753,470 in 2008 (Lop Buri Provincial Office, 2010). The majority of the populace is engaged in the agricultural sector, producing the major crops of rice, sugarcane, cassava, maize, and sunflowers, many of which are grown for export. The province is considered as relatively wealthy among other provinces in Thailand (Felkner & Townsend, 2004) and is ranked 19th out of 76 provinces in GDP per capita (Lop Buri Provincial Office, 2010).

Elevations range from 5-840 meters above sea level, although approximately 65% of the area lies below 100 m. The low-lying areas are found predominantly in the west and scattered among the northeast. Areas of elevation between 100-300 m make up approximately 25% of the province and are located in the northern, central, and eastern regions, while the remaining points make up 10% of the province and are dispersed in the central and eastern regions. The majority of the province is flat with slope of 1% or less.

The landscape is mainly comprised of agricultural usages with the major land covers being rice paddies, upland crops (e.g. cassava, sugarcane, maize, and sunflowers), water, forests and urban areas (Patarasuk & Binford, 2012). Land-cover has undergone considerable alteration over the past several decades. The majority of the change has been from forest to upland crops, a change experienced by about 15% of the entire province between 1989-2006. Other notable land-cover changes in the area include rice paddies to upland crops (8% of the study area), forest to rice (3% of the study area), and forest to built-up (1% of the study area) (Patarasuk & Binford, 2012).

The road network consists of national highways, provincial highways, and local roads. The network is not of even density throughout the province. The greatest densities are found in the southwestern and northern portions of the province. Towards the end of 1990s, some roads were removed following the construction of the Pa Sak Dam and its reservoir between 1994 and completed in 1999.

Methods

Road Network Data

Road network data were compiled from three different Thai agencies: Department of Highways, Department of Rural Roads, and Department of Environmental Quality Promotion. They were geo-referenced to Landsat images with a root mean square (RMS) error of <15 m. Ancillary data such as topographic maps (1:50000 scale) and aerial photographs were used to help geo-reference the road networks. These road layers were combined and topology corrected in ArcGIS version 9.3.

Land Cover Data

Land cover change data were based on the previous study by Patarasuk and Binford (2012). Land-cover classification was based on a hybrid method classification of satellite images of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+) images from 20 January 1989 (TM 4), 10 March 1998 (TM 5), and 8 March 2006 (ETM+). In this analysis, seven land-cover types were classified; forest, water, plantation, rice upland crops (e.g. cassava, sugarcane, maize, and sunflowers), built-up areas, and clouds (including cloud shadows). Clouds were included as a class because the 2006 image possessed approximately 3.5% cloud cover. The corresponding areas of the 1989 and 1998 images were also set as cloud cover to remain consistent over the three dates. Land-cover classification from the previous study had overall accuracy of 83% (Patarasuk & Binford, 2012).

Intensive Study Areas Selections

The notion of using intensive study areas (ISAs) to study the relationships between road network connectivity and land-cover dynamic was adapted from Mondal's and Rojnkureesatien's studies (Mondal, 2011; Rojnkureesatien, 2006). Fifty-six ISAs were randomly selected in space to capture various road network configurations as well as to compare different stages of road network development through time. Each ISA is a square with a total area of 36 km^2 (6x6 km). These selected ISAs were separated into four groups as follows (Figure 4-1):

- Group 1 (ISA 1 to 16) – represents the ISAs that had not undergone road network development.
- Group 2 (ISA 17 to 32) – denotes changes of road network between both 1989-1998 and 1998-2006.
- Group 3 (ISA 33 to 48) – indicates the ISAs that had changes of road network between 1989-1998 and no changes between 1998-2006.
- Group 4 (ISA 49 to 56) – refers to the ISAs that had no changes of road network between 1989-1998 and changes between 1998-2006.

Graph Theory-Based Measures and Indices

This study uses graph theory-based concepts by employing alpha (*α)*, beta (*β)*, and gamma (*γ*) indices to determine road connectivity. These indices are commonly used as measures of the levels of circuitry, complexity, or connectivity (defined below), respectively, in a network. In general, the higher the values of these indices, the higher degree of circuitry, complexity, and connectivity. Connectivity index algorithms used in the study are based on planar graphs, or graphs which can be made to lie in a plane such that no edges intersect at a point other than a node/vertex (Morlok, 1967), are employed. In this study, an edge (or link) refers to a road segment and a node (or vertex) refers a point of an intersection where at least two road segments meet. Each of these indices was calculated for 1989, 1998 and 2006 to measure the dynamic of road connectivity over time. Description of each index is illustrated below.

The alpha index (α) measures the circuitry of a network, or the degree to which it provides alternative paths for traveling from one node to another. It expresses the number of circuits (cycles) in a network in proportion to the maximum possible number of circuits (Equation 1), and can also be used as a measure of the redundancy or duplication in the road network (Kansky, 1963; Kofi, 2010). The index usually ranges from 0 to 1, but can be also expressed by percentage. The higher the α value, the higher the connectivity of a network. When $\alpha = 1$ (or 100%), it describes a completely connected network, which occurs rarely in reality (Rodrigue, et al., 2009; Taaffe, Gauthier, & O'Kelly, 1996). Note that negative values can be derived when a network has a very low level of circuitry (Haggett, Cliff, & Frey, 1977; Kofi, 2010). An example of where a road network can yield a negative value is shown by Vinod et al's (2011) study in Kasaragod Taluk in southern India. The connectivity of road network was mainly limited by the stream network where many areas lack bridges connecting roads that are parallel to streams.

The beta index (β) reflects the complexity and completeness of a network (Kansky, 1963; Morlok, 1967), by expressing the ratio of links to nodes (Equation 2). $\beta < 1$ indicates a disconnected network (e.g. a tree pattern); $\beta = 1$ a single circuit; $\beta > 1$ implies greater complexity of network connectivity (i.e., more than one circuit). The minimum value of β is 0 and the maximum is 3. For a network comprised of a fixed number of nodes, the higher the number of links, the higher the number of paths possible in the network (Coffin, 2009; Rodrigue, et al., 2009; ShiLiang, et al., 2007).

Likewise, increased connectivity achieved by decreasing the numbers of nodes yields higher *β* value; thus, higher connectivity (Kansky, 1963).

The gamma index (*γ*) is a measure of the extent to which the nodes are connected, and is called connectivity (Kansky, 1963; Morlok, 1967). It yields the ratio between the links and nodes of a given network. The index compares the number of links in a given network to the maximum number of links between nodes. The maximum number of links is expressed as 3(*V*-2), where *V* is the number of nodes (Equation 3). Thus, the gamma index is calculated by dividing the number of links (*L*) by the maximum number of links, 3(*V*-2) (Rojnkureesatien, 2006; Taaffe & Gauthier, 1973). Gamma index values range between 0 and 1 (or percentages) and are independent of the number of nodes within a graph (Kansky, 1963). A value of 1 denotes a completely connected network (this case would be extremely unusual and no examples were found in the literature). Note that *γ* can be calculated only for any planar network of more than two nodes (Taaffe & Gauthier, 1973).

Network indices: *α, β,* and *γ* have the following equations:

(1)

(2)

(3)

Where, *L* = number of links

V = number of nodes

As these indices are all based on two variables describing the connectivity of a graph, in this case the connectivity of road network in Lop Buri province, they covary strongly (Morlok, 1967). The indices derived from each ISA were measured with the extension of 3 km buffer from each ISA boundary. This distance was chosen because the previous study by Patarasuk and Binford (2012) found that the majority of land-cover changes occur within 6 km of roads. Thus, buffering at 3 km from each ISA will yield 6 km distance from the center of each ISA. Also, this buffered area intends to capture the connectivity in a bigger scale and to minimize the edge effect around the ISA (Figure 4-3).

Statistical Analysis

The statistical analysis was performed by using SPSS version 18. Two non-parametric statistical tests were performed, as the data were not normally distributed. The Smirnova Test for Normality was employed prior to these analysis to decide which type of test (parametric vs. non-parametric) should be used in this study (Field, 2009). First, the Kendall's Tau (T) test for correlation analysis was used to examine the relationships between road network indices and land cover.

Second, the Wilcoxon matched pair test was performed to determine any significant changes of land cover before and after road network development. ISAs in Group 1 were used as a control group because no road network development occurred within these ISAs. Land cover information for Group 1 was derived for both 1989-1998 and 1998-2006. Next, ISAs in Groups 2, 3, and 4 were used as non-control groups because they had undergone some level of a road network development. Thus, land cover data for 1989-1998 were derived from ISAs within Group 2 and 3 because these ISAs have undergone road network development during this period. Likewise, land cover information of ISAs within Group 2 and 4, were used for the statistical analysis for the period of 1998-2006. Comparing results between control and non-control groups can avoid biases (Andam, Ferraro, Pfaff, Sanchez-Azofeifa, & Robalino, 2008). In this case, the comparisons were made whether roads play a more significant role in which type of land-cover change and in which time period.

Results

General Description of the Road Network

The provincial road network developed most extensively in the northern two-thirds of the province between 1989-2006. Expansion of roads was more extensive between 1989-1998 (increase from 3,347 km to 4,541 km), than 1998-2006 (4,541 km to 4,723 km) (Figure 4-2 and Table 4-1). The minimum and maximum road length in 1989 for each ISA group is Group 1: 12-83 km; Group 2: 16-112 km; Group 3; 27-122 km; and Group 4: 28-136 km. For 1998, the minimum and maximum of total road lengths is Group 1: 12-83 km; Group 2: 34-150 km; Group 3: 55-155 km; and Group 4: 28-136 km**.** Finally, the minimum and maximum total road lengths in 2006 is Group 1: 12-83 km; Group 2: 47-159 km; Group 3: 55-155 km; and Group 4: 32-145 km.

These ISAs are distributed throughout the province. ISAs in Group 1 are primarily found in the southern section of the province where rice and upland crops dominate the landscape. ISAs in Groups 2 and 3 are scattered throughout the northern two-thirds of the province and are comprised mainly of upland crop cultivated fields. Lastly, ISAs in Group 4 occupy the northwest and are characterized by upland crops and forested areas.

Network Connectivity Indices

Table 4-1 reports the numbers of nodes, edges, and total road lengths for the entire province and each individual ISA. Based on these variables, indices were calculated to characterize various aspects of road network connectivity including circuitry, complexity, and connectivity. Lop Buri's provincial road network had approximately 20% circuitry (α = 0.2), medium complexity (β = 1.39) and 47% connectivity (γ = 0.47) in 1989. By 1998 and 2006, these indices have changed little despite the noted increase in total road lengths (Table 4-2).

The derived values of α for some ISAs, especially in 1989, are negative, which is outside of the usual range of 0 (less connected) to 1 (most connected). Negative values imply that that a particular ISA has a disconnected network in terms of circuitry. This usually happens when not all the nodes are connected. ISA 3, ISA 16, ISA 26, and ISA 40 are examples of disconnected networks returning negative α (Figure 4-3). ISA 3 has a disconnected road network and it is located along a river (Figure 4-1). The configuration of this particular network is that there are two major roads that run north-south direction and parallel to each other, separated by the river with few connecting bridges. The majority of land cover in ISA 3 is rice. ISAs 16, 26 and 40, are all located in rural areas where the majority of the land-cover is agriculture (upland crops and rice) and forested areas. These three ISAs are notable for their decline in forest and increase in upland crops. Note that the major road within ISA 16 leads to a protected area in the upper northeast of the province.

In general, as the road network was extended over the period of study, α increased, indicating greater connectivity through an increase in circuitry and alternative paths to travel, as illustrated by ISAs 17 and 40 (Figure 4-4). These are rural-agricultural areas from which roads have been largely extended into the agricultural hinterland. Among these 56 ISAs, ISA 4 and ISA 3 return the highest and lowest α values of, 0.21 and -0.19 respectively in 1989 (Figures 4-3 and 4-5). ISA 4 encompasses the major provincial city of Lop Buri City itself. Most roads are connected because of the shorter streets and multiple intersections in urban setting. The greatest increase in connectivity is witnessed in ISA 40 where the index improved from α = -0.11 and α = 0.08 between 1989 and 1998. Such increases are associated with a greater number of choices of alternative paths from one place to another within a network.

The β index indicates that ISAs 4 and 24 report the greatest degrees of complexity (β = 1.41) and least (β = 0.5) in 1989. By 1998, the minimum, computed for ISA 3, had risen to 0.62 and these extremes remained unchanged in 2006. The urban nature of ISA 4 ensures that roads are very well connected, while the connectivity within ISA 3 is restricted by the presence the river and the limited number of bridging points. Only one road passed through ISA 24 in 1989 creating an unconnected network. In general, as a road network develops, so does its complexity; and connectivity, as displayed by; for example, ISA 31 (Figure 4-5) which reported values of 0.91, 1.06 and 1.08 in 1998, 1989 and 2006 respectively. The majority of roads that were built in 1998 and 2006 in this agricultural area was linked to existing roads; thus, connectivity increased.

Values of γ evince similar patterns to those of α and β, suggesting greater levels of network connectivity over time. Overall, all 56 ISAs have less than 50% road connectivity. One notable exception is ISA 24 (Figure 4-6). In 1989 no value of γ could be estimated because only two nodes and a single edge existed. The number of edges has increased subsequently permitting the computation of γ = 0.34. In 1989, 1998 and

2006, ISA 4 exhibits the highest γ value (γ = 0.48) closely followed by ISA 5 (γ = 0.47). In contrast, ISA 3 shows the lowest connectivity among the 56 ISAs (γ = 0.22)

In general, α, β, and γ values are all positively associated and usually increase as roads are developed. However, some ISAs such as 34 and 45 (Figure 4-7), exhibit constant, or slightly decreased (with only 1-2%) values, despite an increase in total road length. These are mostly agricultural areas on the edges of the two biggest cities in Lop Buri and the decline occurs when networks are simply extended into hinterland as dead-ends rather than linking two existing roads.

Road Network, Connectivity Indices and Land-Cover Distribution

Land-cover distribution for the entire province is shown in Figure 4-8 and in percentages of each land-cover type for each ISA are shown in Tables 4-3 to 4-5. Two different statistical analyses were performed to examine the relationships between road network, connectivity and land-cover distribution. First, correlation analysis determined whether changes of road network indices were significantly associated to changes in percentage of each type of land cover. Several correlation analysis matrices were calculated for all 56 ISAs as well as ISAs within each individual group. Kendall's Tau (T), 1-tailed, test was used to identify relationships of road network development and land-cover change at different stages. A negative statistic indicates that the greater the changes of α, β, and γ between time periods the smaller the percentage change in land cover. A positive value for T indicates that values of the parameters and percentages change in the same direction Perfect positive (negative) correlations are indicated by scores of 1 (-1), (Tables 4-6 to 4-9).

Employing all ISAs, results suggest that changes of forest, upland crops, and built-up areas are significantly correlated in changes of *α* and *β* values (Table 4-6). Only results significant at the 95% confidence interval are discussed. This association was more evident during the period 1989-1998 than 1998-2006. Forest cover was negatively associated with the parameters, whereas upland crops and built-up areas showed positive relationships. Thus, higher changes of circuitry (*α)* and complexity (*β*) are associated with loss of forest cover; and an increase in upland crops and built-up areas. Analyses for ISAs within each individual group revealed that the relationships between network indices and changes in land-cover are varied between groups. When road development in Lop Buri continuously occurred from 1989 to 2006 (as in the case of ISAs 17-32 in Group 2), only built-up area is positively correlated with changes in *α* between 1989-1998 (Table 4-7). Changes in water cover are negatively correlated with all three parameters, especially during 1998-2006. However, when roads were developed for only one time period, (1989-1998 in ISAs 33-48 in Group 3 or 1998-2006 for ISAs 49-56 in Group 4, changes in the amount of built-up areas is positively related with changes in *α*, *β, a*nd *γ* values. for the earlier period (Table 4-8). while between, water and rice have dominate the correlations in the latter. Water was negatively correlated, and rice paddies positively, with changes in all three parameters (Table 4-9).

The Wilcoxon matched pair test was used to complete ‘before and after’ comparisons of road network development to the amount of land cover. Matched pairs for each time step and for each type of land cover were derived, yielding a total of 12 pairs each for control and non-control groups (Tables 4-10 and 4-11). The results from the control group (Table 4-10) showed that plantation and rice between 1989-

1998,forest, upland crops and built-up areas between 1998-2006 were significantly changed even though no road development occurred within this group. The results implied that changes of these types of land-cover are largely influenced by various factors other than roads. When adding roads onto the network for those ISAs within Groups 2, 3, and 4, the results revealed that roads significantly influenced changes of every type of land-cover except for water during 1989-1998 (Table 4-11).

Discussion

The results clearly show the increase in total road length in Lop Buri province from 1989 to 2006 however, network connectivity has not improved greatly; in fact it appears to remain practically unchanged. For each individual ISA, the initial road connectivity (i.e., in 1989) changed according to the individual location and geographical features. Some ISAs are well connected because they are within a city (e.g. ISAs 4 and 5) others are very poorly connected due to a geographical feature such as a river or mountain (e.g. ISA 3). In general, road connectivity has increased in association with the extended road networks of 1998 and 2006, yet, a few ISAs showed a decline in connectivity. Thus, results do not fully support the first hypothesis that as road networks are developed, connectivity increases, yet they are consistent with those of Coffin (2009) in the Santa Fe River watershed in Florida, USA.

The changes in connectivity might result from the geographical location of the areas in which development takes place. Connectivity improves greatly when new roads connect to the existing road system. On the other hand, it remains unchanged or declines when development extends into the agricultural hinterland producing dead-end roads, as the ratios and numbers of nodes and links are employed in the calculations of α, β, γ indices, remain fairly constant. Dead-end roads generate a disproportionate number of nodes in comparison to links, resulting in a decrease of network indices. No single pattern of improving or declining connectivity could be identified in ISAs within Lop Buri province. As mentioned earlier, roads in Lop Buri province were extended in the northern two-thirds of the province; thus, changes (increase or decrease) in road network indices are most abundant within this region, particularly amongst ISAs within Group 2, 3 and 4.

Road network development in Thailand was intentionally done to foster social and economic development by facilitating the transportation of commercial crops from agricultural areas to local markets and other major cities (Rojnkureesatien, 2006; Torres, et al., 2004). Improved road network connectivity allows greater choices of alternative paths to destinations, often resulting in reduced transportation time and/or costs, and maximized profits for farmers (Jacoby, 2000; Verburg, et al., 2004). On the other hand, development of roads extending into the hinterland provides access to land, particularly access to a remote areas such as forests. The combination of better road connectivity to market areas and expansion into previously in accessible regions, encourages people to change the landscape. Based on several previous studies, the most prominent landscape change is from forests to agriculture, particularly, in tropical regions like the Southeast Asia or the Amazon (Fox & Vogler, 2005; Perz, et al., 2008).

The use of Kendall's Tau (T) highlights the link between road network development and land cover. The most profound landscape changes in association with improvement of road network connectivity are shown clearly in this study through the loss of forest, increases in upland crop production, and increased in built-up areas. This supports the points of (Nelson & Hellerstein, 1997; Rojnkureesatien, 2006) that roads provided better access for the exploitation of forest resources. In this study, the reduction of forest cover is linked with higher changes of *α* values. The observation that the percentage of built-up area is associated with the connectivity indices, suggests that humans prefer to settle near a road network for better accessibility as the built-up areas in Lop Buri province are almost exclusively human settlements and industrial estates (Hawbaker, Radeloff, Clayton, Hammer, & Gonzalez-Abraham, 2006; Rodrigue, et al., 2009; Schnaiberg, Riera, Turner, & Voss, 2002).

Finally, the Wilcoxon tests revealed some significant changes in land cover following development of the road network, supporting the hypothesis that new roads have an effect upon on the percentages of land under various covers. The most profound changes are noted in forests, plantations rice, upland crops, and built-up areas. This suggests that, the development of road networks facilitate/encourage people to convert land from one cover to another. Upland crops are particularly sensitive as road development allows not only vehicular access to land, but also for the transport of its agricultural products to market areas (Entwisle, et al., 2005; Verburg, et al., 2004). Built-up areas increase with the road network as people prefer to locate near a transportation route that offers better accessibility to a variety of destinations (Buurman & Rietveld, 1999; Feng, Li, & Zhou, 2007).

The study has analyzed how road indices and amount of roads affect land-cover and indicates that road connectivity might not be as important as the amount of roads increase. The correlation analysis implies that only a few land-cover types are significantly linked with changes in road indices. In contrast, the increase the amount of road before and after road development has showed significant changes in the amount of land cover.

Conclusion

This study has examined the relationships between road network development and land-cover dynamics through network connectivity and statistical tests. Objective graph theory based indices are employed to describe the level connectivity and statistical tests performed to examine any differences in the percentages of land cover.

The results show that even though the total length of roads in the study area increases, the connectivity does not always do so. This depends on where roads were developed: whether linking existing roads, or developed as dead-ends. The most evident relationships are between road connectivity and built-up areas and forest cover. Statistical analyses shed light on the fact that road network development can affect the amount of land-cover through time, including rice and upland crops, in addition to forest, and built-up areas.

Road network connectivity is scrutinized at two important spatial scales, provincial and ISAs, and reveal that levels of connectivity differ according to the scales of employ. In part these differences may be attributed to the arbitrary selection of boundaries of the ISAs; thus, at a larger scale, roads within the ISA might actually have greater connectivity to other areas beyond the ISA. A series of general ideas of how road network should be connected or built for a regional or national development such that road development improves the connectivity and link regions together, have been laid out and tested.

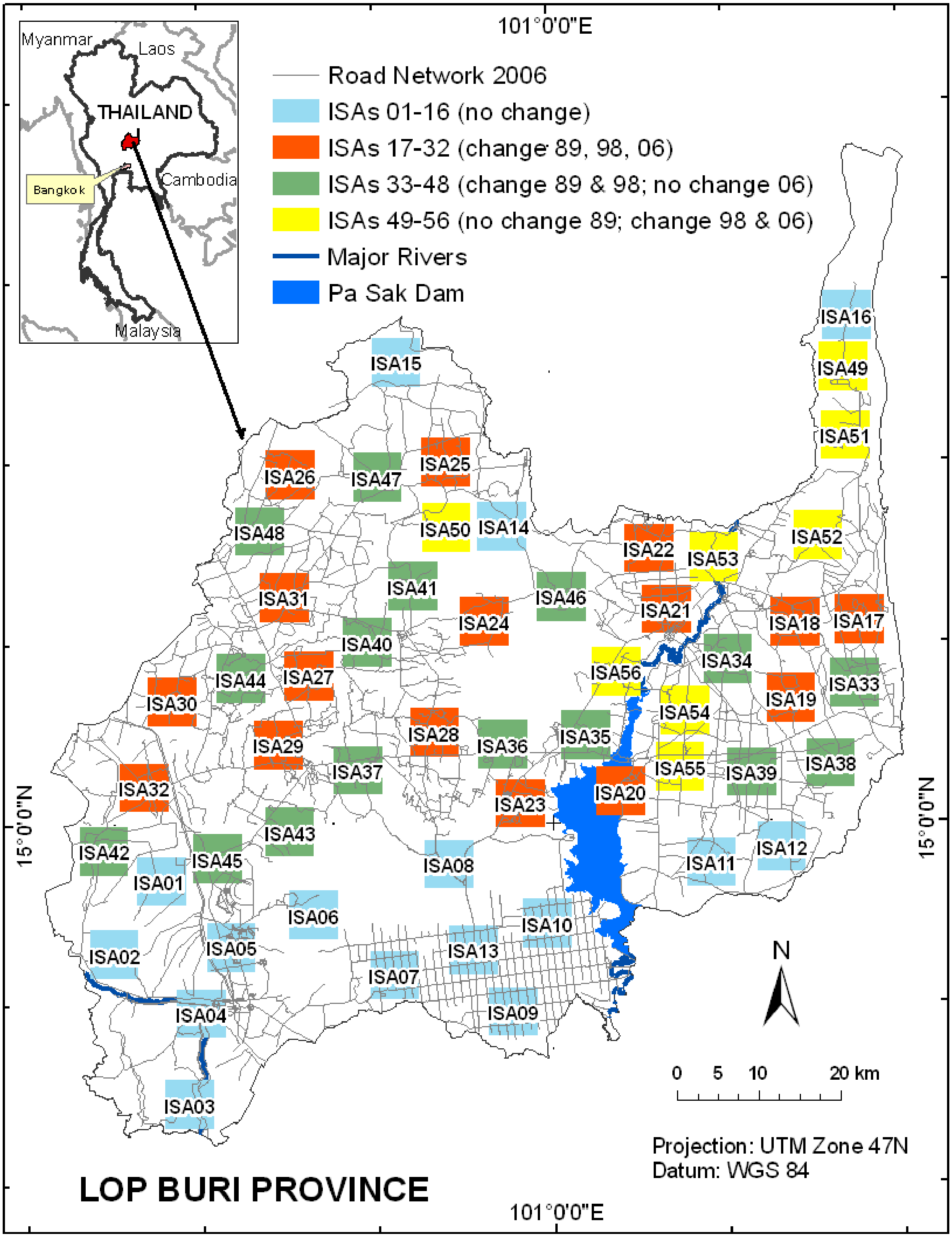


Figure 4-1. The study area and 56 intensive study areas (ISA's).

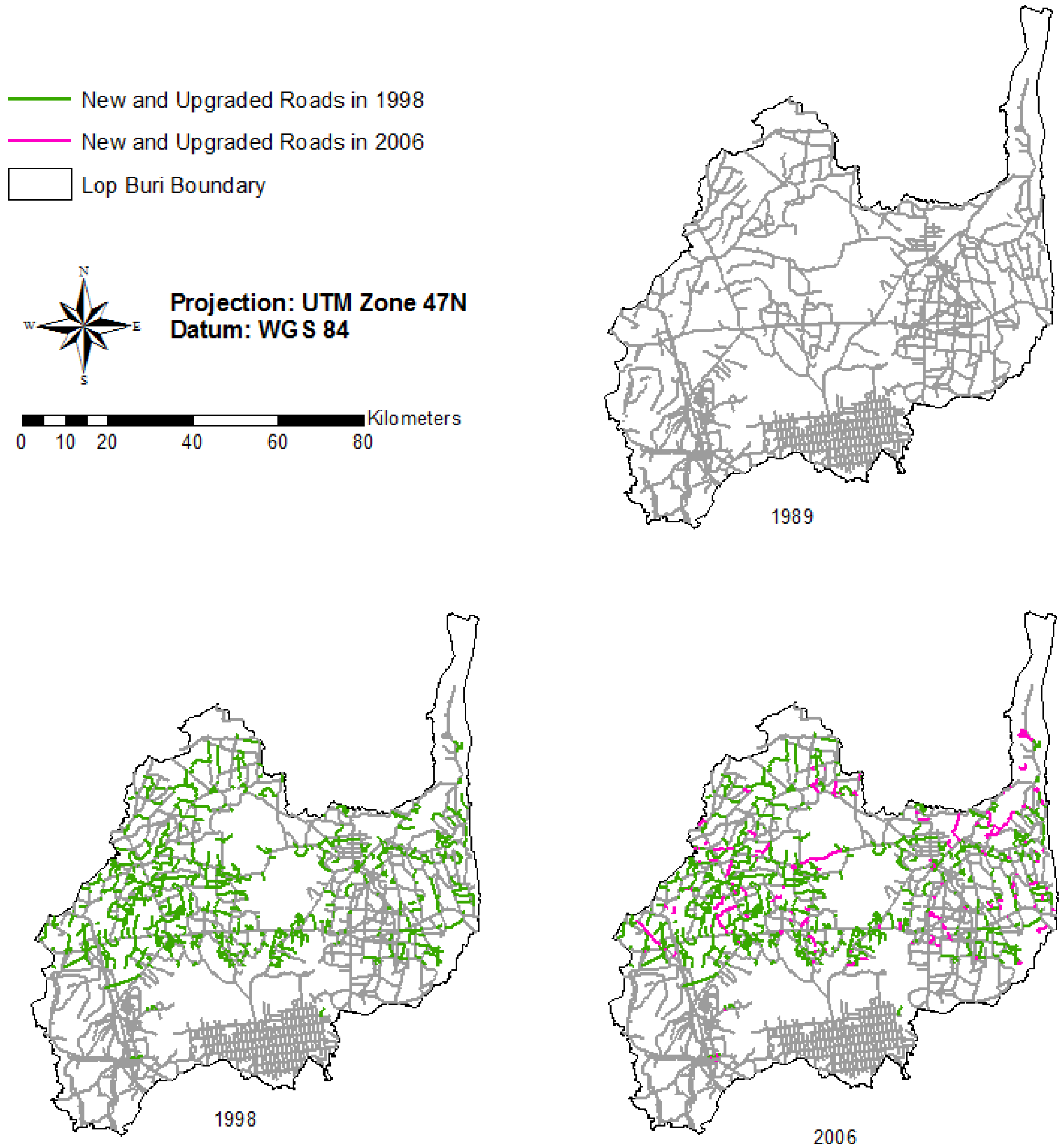


Figure 4-2. Road Network Development

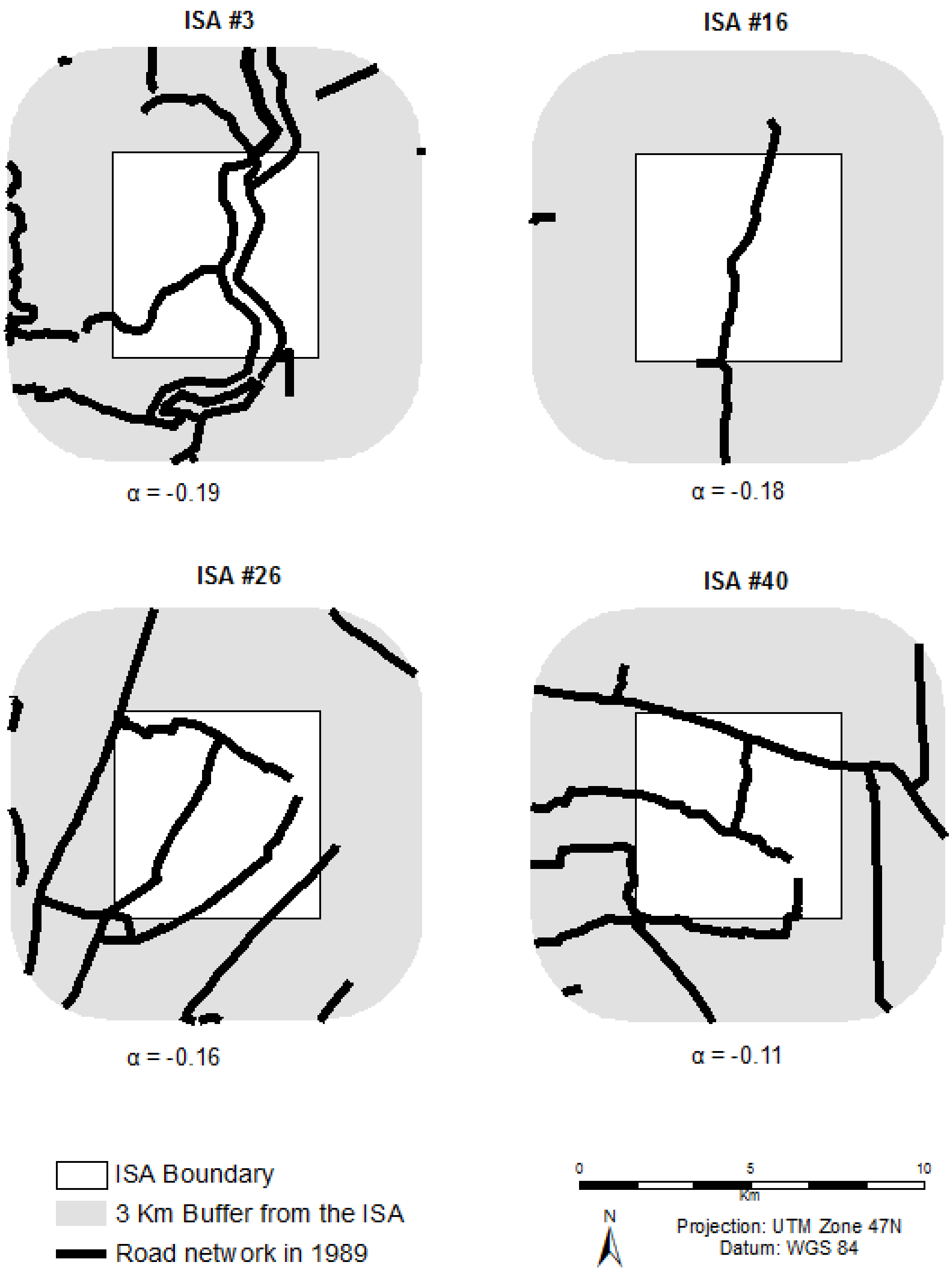


Figure 4-3. Sample ISAs and 3 km buffer. These ISAs had a negative □ in 1989 because the road disconnected within the ISA and buffer.

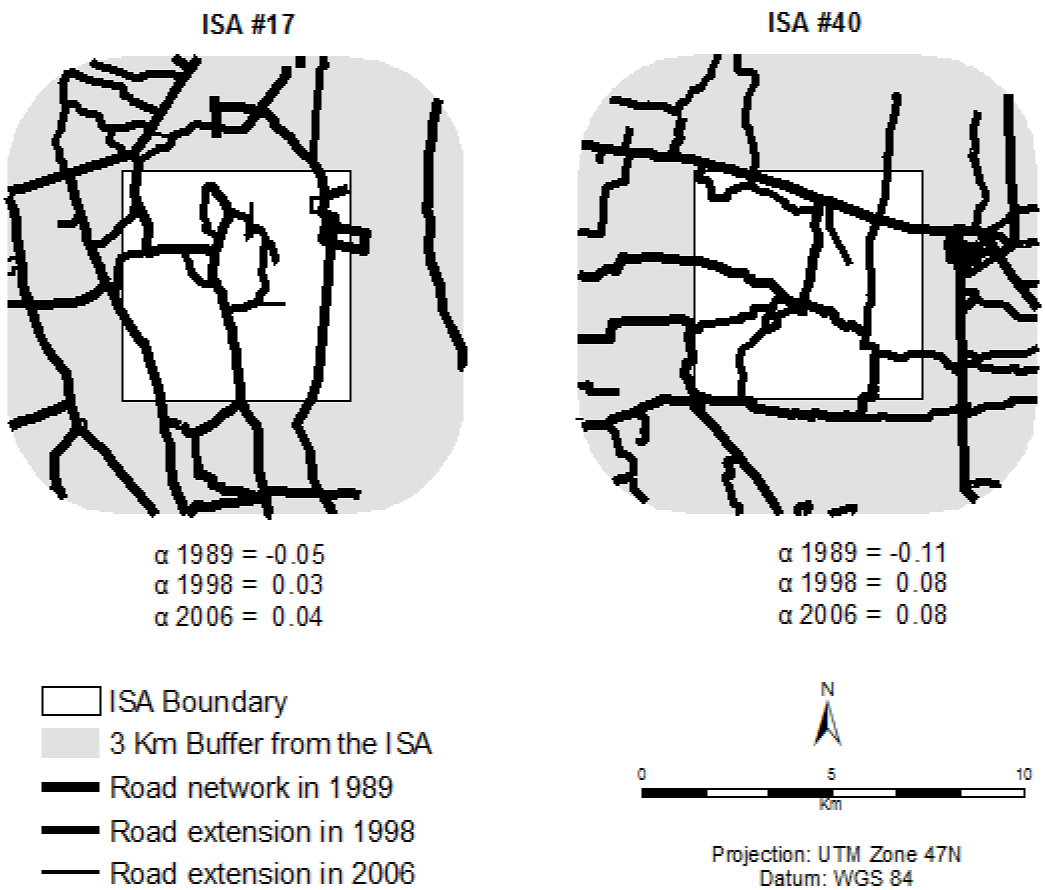


Figure 4-4. Sample ISAs and 3 km buffer. These ISA have α values increased from 1989-2006.

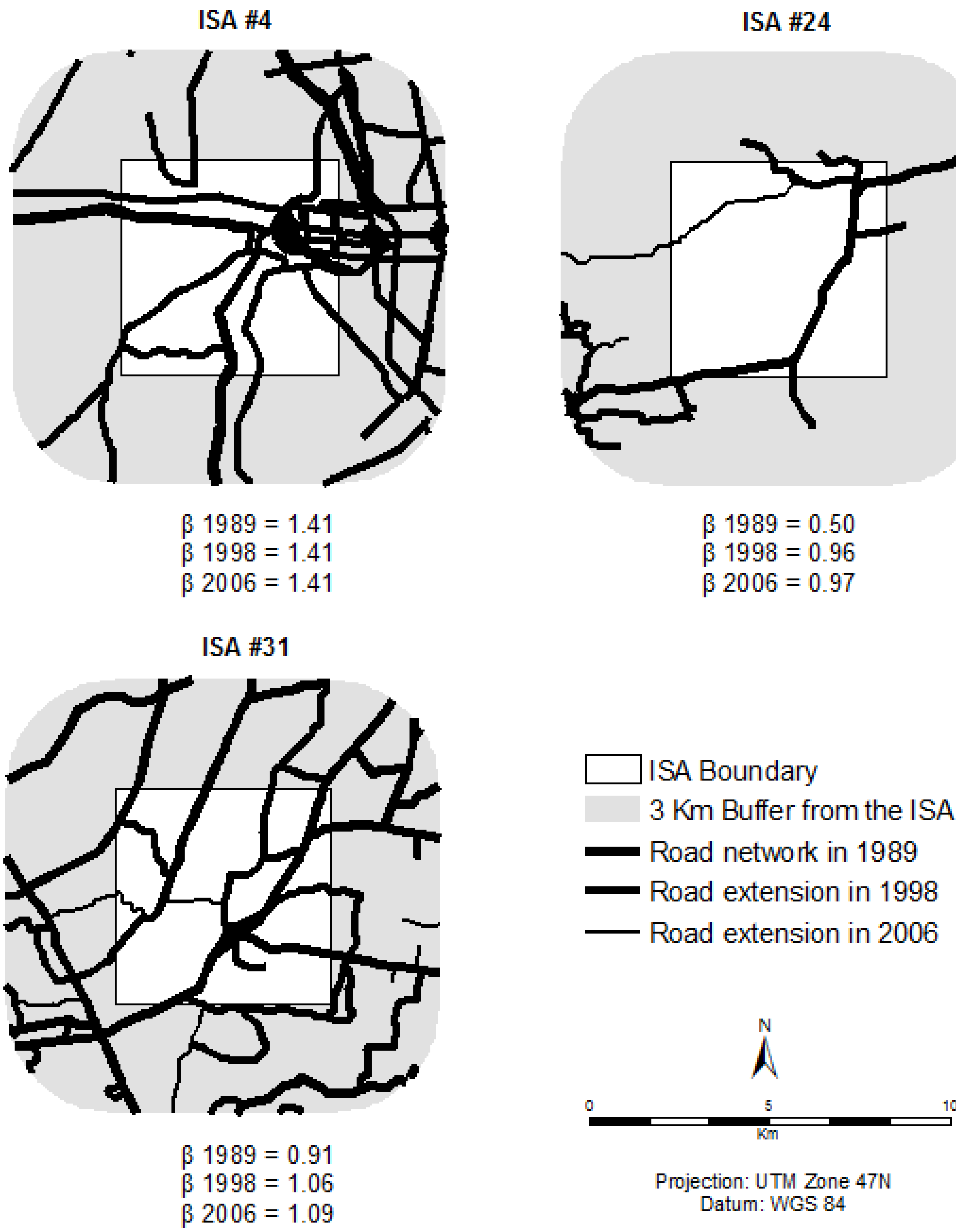


Figure 4-5. Beta index: ISA 4 (highest beta in 1989); ISA 24 (lowest in 1989), and ISA 31 (beta improve through 1989, 1998, and 2006).

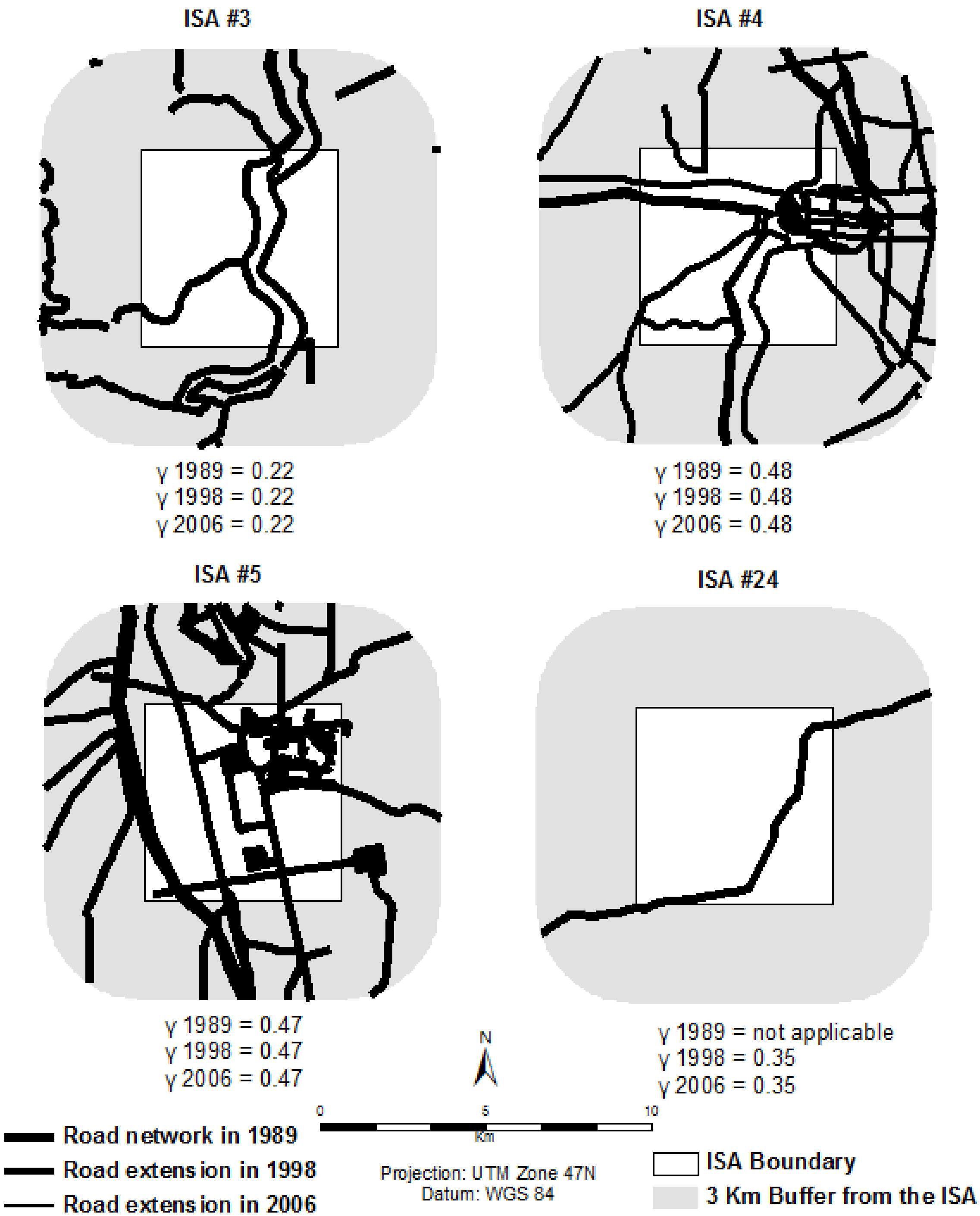


Figure 4-6. Gamma Index: ISA; ISA; ISA 24 (road network in 1989)

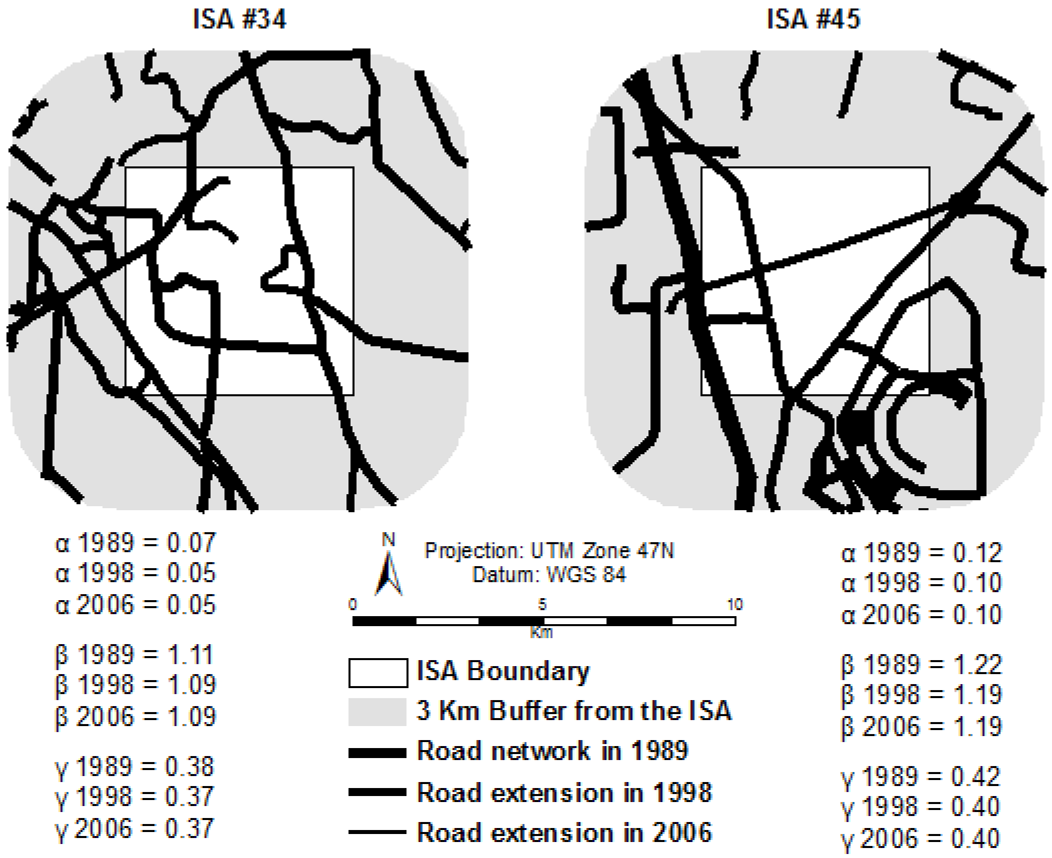


Figure 4-7. Indices decreased

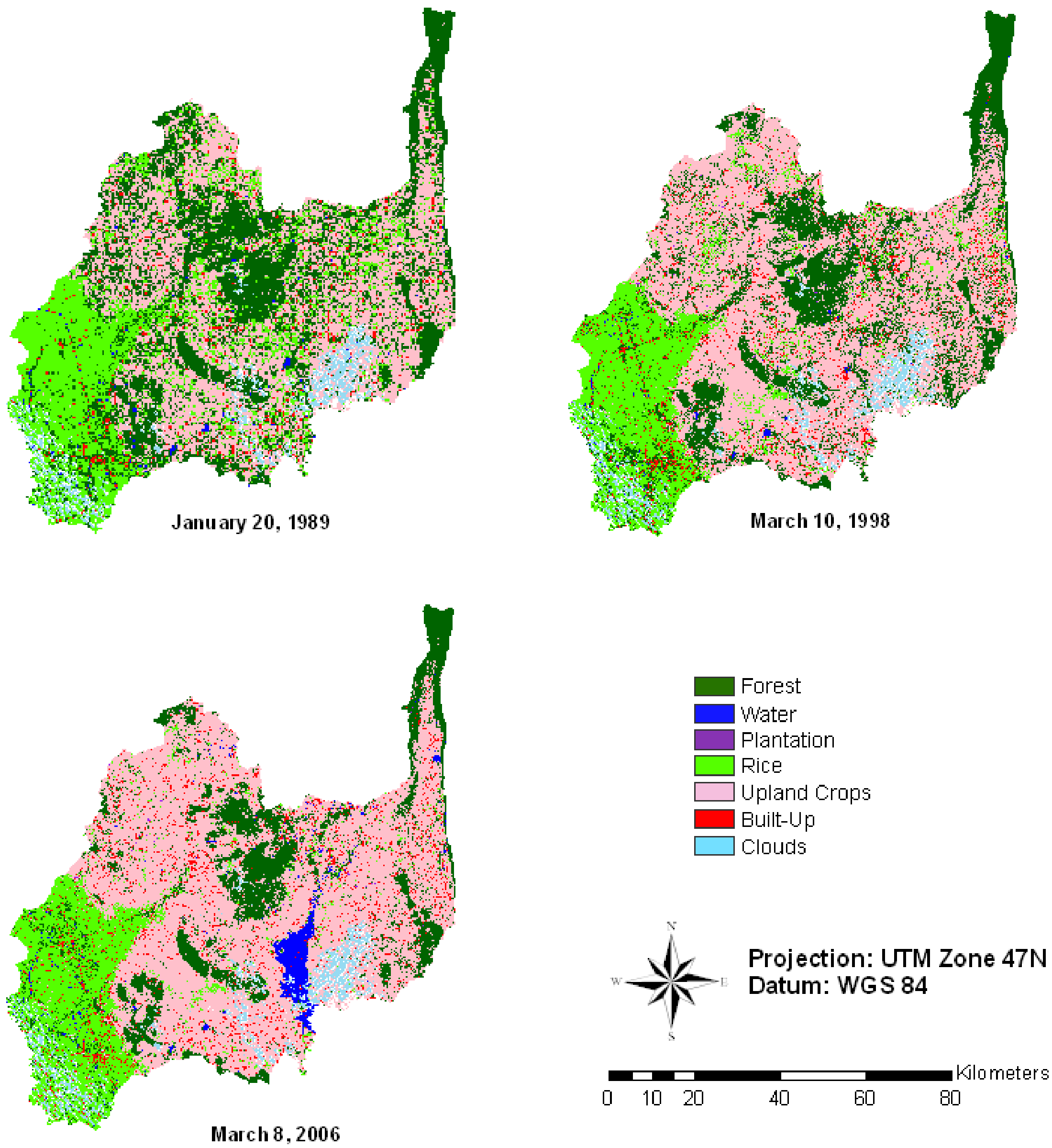


Figure 4-8. Land-cover distribution in Lop Buri province (Patarasuk & Binford, 2012)

Table 4-1. Node, edges and Total Road Lengths of 3 km buffer

Area	1989		1998		2006		Total Road Lengths (km)		
	nodes (V)	edges (L)	nodes (V)	edges (L)	nodes (V)	edges (L)	1989	1998	2006
Entire Province	1,366	1,903	2,474	3,418	2,807	3,869	3,347.42	4,541.16	4,722.97
ISA01	30	28	30	28	30	28	85.12	85.12	85.12
ISA02	30	33	30	33	30	33	65.38	65.38	65.38
ISA03	39	24	39	24	39	24	68.75	68.75	68.75
ISA04	187	264	187	264	187	264	173.73	173.73	173.73
ISA05	235	331	235	331	235	331	183.25	183.25	183.25
ISA06	18	15	18	15	18	15	27.13	27.13	27.13
ISA07	93	116	93	116	93	116	147.00	147.00	147.00
ISA08	18	17	18	17	18	17	36.29	36.29	36.29
ISA09	85	113	85	113	85	113	151.50	151.50	151.50
ISA10	91	126	91	126	91	126	162.04	162.04	162.04
ISA11	37	35	37	35	37	35	77.37	77.37	77.37
ISA12	27	29	27	29	27	29	63.54	63.54	63.54
ISA13	94	129	94	129	94	129	164.79	164.79	164.79
ISA14	7	6	7	6	7	6	28.18	28.18	28.18
ISA15	13	12	13	12	13	12	39.44	39.44	39.44
ISA16	8	5	8	5	8	5	12.17	12.17	12.17
ISA17	48	42	76	80	91	97	83.14	115.55	119.88
ISA18	29	27	65	75	84	96	72.55	107.30	114.99
ISA19	32	29	52	53	67	71	66.28	93.34	101.78
ISA20	50	58	71	84	69	83	88.39	98.35	86.80
ISA21	65	76	136	181	156	204	103.51	150.43	159.08
ISA22	44	42	63	73	69	79	79.06	110.14	113.79
ISA23	23	24	109	125	125	146	46.21	108.78	113.71
ISA24	2	1	25	24	29	28	15.74	43.93	46.74
ISA25	23	19	51	48	66	70	60.46	89.36	100.79
ISA26	27	18	47	42	49	45	53.71	81.41	82.96
ISA27	16	14	82	88	96	105	57.06	126.12	140.95

Table 4-1. Continued

Area	1989		1998		2006		Total Road Lengths (km)		
	nodes (V)	edges (L)	nodes (V)	edges (L)	nodes (V)	edges (L)	1989	1998	2006
ISA28	25	26	92	104	105	120	73.34	120.08	127.72
ISA29	16	17	116	133	136	165	36.60	125.08	145.11
ISA30	26	23	82	85	92	96	58.30	98.66	103.62
ISA31	34	31	80	85	94	102	111.91	124.22	137.03
ISA32	42	46	91	110	94	114	82.98	139.95	146.40
ISA33	30	28	60	69	60	69	70.60	107.75	107.75
ISA34	56	62	85	93	85	93	96.85	115.56	115.56
ISA35	37	35	107	133	107	133	54.35	101.94	101.94
ISA36	29	31	104	114	104	114	42.24	85.71	85.71
ISA37	29	27	121	135	121	135	66.38	125.67	125.67
ISA38	22	23	49	51	49	51	46.66	78.33	78.33
ISA39	62	70	95	116	95	116	115.14	151.21	151.21
ISA40	20	15	101	115	101	115	57.32	130.48	130.48
ISA41	13	10	44	41	44	41	26.74	54.99	54.99
ISA42	30	23	34	28	34	28	70.22	79.58	79.58
ISA43	17	15	40	37	40	37	42.50	72.21	72.21
ISA44	26	23	138	159	138	159	54.83	155.37	155.37
ISA45	90	110	105	125	105	125	122.92	140.14	140.14
ISA46	14	12	34	36	34	36	35.89	59.58	59.58
ISA47	25	24	96	118	96	118	55.92	101.92	101.92
ISA48	28	29	48	53	48	53	70.13	94.13	94.13
ISA49	17	16	17	16	25	28	28.35	28.35	32.30
ISA50	32	28	32	28	44	45	40.40	40.40	47.61
ISA51	26	24	26	24	35	33	37.66	37.66	42.63
ISA52	51	47	51	47	66	65	79.45	79.45	100.84
ISA53	83	96	83	96	92	108	92.78	92.78	102.72
ISA54	77	95	77	95	98	125	136.31	136.31	145.81
ISA55	84	104	84	104	103	130	130.93	130.93	143.64
ISA56	50	48	50	48	57	55	78.82	78.82	82.86

Table 4-2. Alpha, Beta, and Gamma Indices

Area	Alpha (α)			Beta (β)			Gamma (γ)		
	1989	1998	2006	1989	1998	2006	1989	1998	2006
Entire Province	0.20	0.19	0.19	1.39	1.38	1.38	0.47	0.46	0.46
ISA01	-0.02	-0.02	-0.02	0.93	0.93	0.93	0.33	0.33	0.33
ISA02	0.07	0.07	0.07	1.10	1.10	1.10	0.39	0.39	0.39
ISA03	-0.19	-0.19	-0.19	0.62	0.62	0.62	0.22	0.22	0.22
ISA04	0.21	0.21	0.21	1.41	1.41	1.41	0.48	0.48	0.48
ISA05	0.21	0.21	0.21	1.41	1.41	1.41	0.47	0.47	0.47
ISA06	-0.06	-0.06	-0.06	0.83	0.83	0.83	0.31	0.31	0.31
ISA07	0.13	0.13	0.13	1.25	1.25	1.25	0.42	0.42	0.42
ISA08	0.00	0.00	0.00	0.94	0.94	0.94	0.35	0.35	0.35
ISA09	0.18	0.18	0.18	1.33	1.33	1.33	0.45	0.45	0.45
ISA10	0.20	0.20	0.20	1.38	1.38	1.38	0.47	0.47	0.47
ISA11	-0.01	-0.01	-0.01	0.95	0.95	0.95	0.33	0.33	0.33
ISA12	0.06	0.06	0.06	1.07	1.07	1.07	0.39	0.39	0.39
ISA13	0.20	0.20	0.20	1.37	1.37	1.37	0.47	0.47	0.47
ISA14	0.00	0.00	0.00	0.86	0.86	0.86	0.40	0.40	0.40
ISA15	0.00	0.00	0.00	0.92	0.92	0.92	0.36	0.36	0.36
ISA16	-0.18	-0.18	-0.18	0.63	0.63	0.63	0.28	0.28	0.28
ISA17	-0.05	0.03	0.04	0.88	1.05	1.07	0.30	0.36	0.36
ISA18	-0.02	0.09	0.08	0.93	1.15	1.14	0.33	0.40	0.39
ISA19	-0.03	0.02	0.04	0.91	1.02	1.06	0.32	0.35	0.36
ISA20	0.09	0.10	0.11	1.16	1.18	1.20	0.40	0.41	0.41
ISA21	0.10	0.17	0.16	1.17	1.33	1.31	0.40	0.45	0.44
ISA22	-0.01	0.09	0.08	0.95	1.16	1.14	0.33	0.40	0.39
ISA23	0.05	0.08	0.09	1.04	1.15	1.17	0.38	0.39	0.40
ISA24	0.00	0.00	0.00	0.50	0.96	0.97	n/a	0.35	0.35
ISA25	-0.07	-0.02	0.04	0.83	0.94	1.06	0.30	0.33	0.36
ISA26	-0.16	-0.04	-0.03	0.67	0.89	0.92	0.24	0.31	0.32
ISA27	-0.04	0.04	0.05	0.88	1.07	1.09	0.33	0.37	0.37
ISA28	0.04	0.07	0.08	1.04	1.13	1.14	0.38	0.39	0.39
ISA29	0.07	0.08	0.11	1.06	1.15	1.21	0.40	0.39	0.41
ISA30	-0.04	0.03	0.03	0.88	1.04	1.04	0.32	0.35	0.36
ISA31	-0.03	0.04	0.05	0.91	1.06	1.09	0.32	0.36	0.37
ISA32	0.06	0.11	0.11	1.10	1.21	1.21	0.38	0.41	0.41
ISA33	-0.02	0.09	0.09	0.93	1.15	1.15	0.33	0.40	0.40
ISA34	0.07	0.05	0.05	1.11	1.09	1.09	0.38	0.37	0.37
ISA35	-0.01	0.13	0.13	0.95	1.24	1.24	0.33	0.42	0.42
ISA36	0.06	0.05	0.05	1.07	1.10	1.10	0.38	0.37	0.37
ISA37	-0.02	0.06	0.06	0.93	1.12	1.12	0.33	0.38	0.38
ISA38	0.05	0.03	0.03	1.05	1.04	1.04	0.38	0.36	0.36
ISA39	0.08	0.12	0.12	1.13	1.22	1.22	0.39	0.42	0.42

Table 4-2. Continued

Area	Alpha (α)			Beta (β)			Gamma (γ)		
	1989	1998	2006	1989	1998	2006	1989	1998	2006
ISA40	-0.11	0.08	0.08	0.75	1.14	1.14	0.28	0.39	0.39
ISA41	-0.10	-0.02	-0.02	0.77	0.93	0.93	0.30	0.33	0.33
ISA42	-0.11	-0.08	-0.08	0.77	0.82	0.82	0.27	0.29	0.29
ISA43	-0.03	-0.03	-0.03	0.88	0.93	0.93	0.33	0.32	0.32
ISA44	-0.04	0.08	0.08	0.88	1.15	1.15	0.32	0.39	0.39
ISA45	0.12	0.10	0.10	1.22	1.19	1.19	0.42	0.40	0.40
ISA46	-0.04	0.05	0.05	0.86	1.06	1.06	0.33	0.38	0.38
ISA47	0.00	0.12	0.12	0.96	1.23	1.23	0.35	0.42	0.42
ISA48	0.04	0.07	0.07	1.04	1.10	1.10	0.37	0.38	0.38
ISA49	0.00	0.00	0.09	0.94	0.94	1.12	0.36	0.36	0.41
ISA50	-0.05	-0.05	0.02	0.88	0.88	1.02	0.31	0.31	0.36
ISA51	-0.02	-0.02	-0.02	0.92	0.92	0.94	0.33	0.33	0.33
ISA52	-0.03	-0.03	0.00	0.92	0.92	0.98	0.32	0.32	0.34
ISA53	0.09	0.09	0.09	1.16	1.16	1.17	0.40	0.40	0.40
ISA54	0.13	0.13	0.15	1.23	1.23	1.28	0.42	0.42	0.43
ISA55	0.13	0.13	0.14	1.24	1.24	1.26	0.42	0.42	0.43
ISA56	-0.01	-0.01	-0.01	0.96	0.96	0.96	0.33	0.33	0.33

Table 4-3. Land-Cover Distribution (in Percentage), 1989

ISAs	% Clouds	% Forest	% Water	% Plantation	% Rice	% Upland Crops	% Built-up
Entire Province	3.41	33	0.52	0	23.14	36.96	2.97
ISA01	0.00	5.21	0.02	0.00	92.43	0.03	2.31
ISA02	20.77	9.86	0.32	0.00	68.17	0.07	0.81
ISA03	28.33	15.05	0.12	0.00	54.78	0.05	1.68
ISA04	2.29	37.18	1.23	0.00	49.97	0.05	9.26
ISA05	0.45	36.04	0.85	0.00	49.45	3.12	10.09
ISA06	2.75	53.79	3.56	0.00	5.96	32.09	1.85
ISA07	0.03	25.13	0.73	0.00	8.80	58.83	6.48
ISA08	0.46	37.96	0.12	0.00	5.09	54.38	1.99
ISA09	11.71	26.01	0.78	0.00	9.50	45.97	6.03
ISA10	4.03	20.23	0.77	0.00	23.05	43.16	8.75
ISA11	33.65	6.57	0.64	0.00	6.61	49.56	2.97
ISA12	0.28	35.18	0.58	0.00	5.21	56.44	2.30
ISA13	7.90	16.31	0.37	0.00	17.61	50.84	6.97
ISA14	0.00	54.46	0.22	0.00	10.31	32.73	2.27
ISA15	0.00	56.42	0.05	0.00	8.52	33.42	1.58
ISA16	0.00	72.53	0.02	0.00	3.90	22.55	1.00
ISA17	0.00	24.65	1.26	0.00	6.46	63.50	4.14
ISA18	0.11	25.43	0.18	0.00	7.96	63.23	3.09
ISA19	0.00	28.65	0.05	0.00	7.22	62.17	1.90
ISA20	0.73	26.34	0.69	0.00	19.08	49.29	3.86
ISA21	0.04	36.00	0.73	0.00	9.30	46.71	7.22
ISA22	0.00	34.14	0.34	0.00	14.65	46.93	3.93
ISA23	1.69	12.26	0.03	0.00	17.33	65.96	2.74
ISA24	1.69	61.41	0.33	0.00	13.91	20.21	2.45
ISA25	0.00	16.66	0.00	0.00	21.93	56.36	5.05
ISA26	0.00	44.92	0.12	0.00	9.68	42.50	2.76
ISA27	0.00	34.08	0.01	0.00	4.55	59.27	2.09
ISA28	0.68	17.99	0.19	0.00	11.99	63.56	5.59
ISA29	0.00	21.92	0.53	0.00	73.06	2.47	2.02
ISA30	0.00	3.72	0.00	0.00	93.56	1.25	1.46
ISA31	0.00	31.26	0.05	0.00	2.97	63.30	2.42
ISA32	0.00	11.89	0.50	0.00	83.61	0.08	3.92
ISA33	0.00	29.16	0.03	0.00	4.16	63.55	3.11
ISA34	0.00	22.98	0.19	0.00	18.26	54.77	3.80
ISA35	0.00	28.69	0.03	0.00	16.50	48.03	6.75
ISA36	0.00	54.76	0.19	0.00	13.80	27.26	3.99
ISA37	0.09	46.03	0.21	0.00	16.25	33.85	3.57
ISA38	0.00	52.02	0.01	0.00	6.32	39.26	2.38
ISA39	12.79	16.03	0.17	0.00	10.27	57.15	3.58
ISA40	0.00	38.59	0.35	0.00	3.61	55.50	1.95

Table 4-3. Continued

ISAs	% Clouds	% Forest	% Water	% Plantation	% Rice	% Upland Crops	% Built-up
ISA41	0.00	68.98	0.90	0.00	8.54	20.34	1.24
ISA42	0.00	8.60	4.15	0.00	84.90	0.03	2.32
ISA43	0.00	34.08	0.00	0.00	15.81	47.74	2.37
ISA44	0.00	36.83	0.00	0.00	10.57	50.57	2.03
ISA45	0.00	15.56	0.73	0.00	79.75	0.52	3.44
ISA46	0.00	53.62	0.24	0.00	14.14	30.14	1.86
ISA47	0.00	36.76	0.70	0.00	14.67	44.55	3.31
ISA48	0.00	34.07	0.18	0.00	5.45	58.00	2.31
ISA49	0.00	57.64	0.11	0.00	5.70	34.97	1.58
ISA50	0.00	57.57	0.12	0.00	9.91	30.95	1.45
ISA51	0.00	42.15	0.00	0.00	5.53	50.64	1.68
ISA52	0.00	39.31	0.02	0.00	7.17	51.83	1.66
ISA53	0.00	39.29	0.25	0.00	21.24	36.62	2.60
ISA54	0.00	17.33	0.02	0.00	13.91	64.87	3.87
ISA55	6.70	13.87	0.91	0.00	10.43	63.73	4.37
ISA56	0.00	37.89	0.72	0.00	14.11	41.06	6.22

Table 4-4. Land-Cover Distribution (in Percentage), 1998

ISAs	% Clouds	% Forest	% Water	% Plantation	% Rice	% Upland Crops	% Built-up
Entire Province	3.41	25.04	0.39	0.08	17.18	49.45	4.46
ISA01	0.00	2.82	0.37	0.00	93.07	0.19	3.55
ISA02	20.77	15.09	1.53	0.02	60.43	0.09	2.06
ISA03	28.33	12.36	0.83	0.00	53.25	0.02	5.22
ISA04	2.29	28.64	2.88	0.00	51.58	0.08	14.52
ISA05	0.45	14.36	0.23	0.00	65.39	6.31	13.26
ISA06	2.75	52.39	2.02	0.22	1.27	40.29	1.05
ISA07	0.03	16.27	0.22	0.06	10.74	65.09	7.59
ISA08	0.46	36.67	0.39	0.26	20.60	39.26	2.37
ISA09	11.71	12.71	0.02	0.00	7.72	60.61	7.23
ISA10	4.03	7.36	0.04	0.00	0.66	81.27	6.65
ISA11	33.65	11.82	0.05	0.01	2.03	50.64	1.79
ISA12	0.28	48.93	0.22	0.02	0.13	48.86	1.56
ISA13	7.90	10.04	0.11	0.00	1.29	71.53	9.13
ISA14	0.00	69.11	0.78	0.04	1.50	26.62	1.95
ISA15	0.00	41.29	0.02	0.42	5.23	51.69	1.35
ISA16	0.00	92.42	0.19	0.03	0.02	6.60	0.74
ISA17	0.00	16.30	0.80	0.03	11.31	60.16	11.39
ISA18	0.11	18.71	0.10	0.04	4.35	71.61	5.09
ISA19	0.00	31.07	0.22	0.11	1.16	65.01	2.42
ISA20	0.73	18.81	0.68	0.12	3.86	71.71	4.10
ISA21	0.04	25.92	0.42	0.00	7.93	53.88	11.81
ISA22	0.00	28.90	0.13	0.05	5.62	59.08	6.22
ISA23	1.69	11.36	0.00	0.01	2.39	79.08	5.47
ISA24	1.69	47.31	0.06	0.03	4.14	44.55	2.23
ISA25	0.00	10.63	0.75	0.01	10.37	73.10	5.14
ISA26	0.00	20.39	0.00	0.13	2.08	72.22	5.18
ISA27	0.00	12.11	0.00	0.04	5.08	78.55	4.22
ISA28	0.68	14.11	0.06	0.00	4.71	73.86	6.56
ISA29	0.00	12.99	0.06	0.01	77.27	3.40	6.27
ISA30	0.00	10.08	0.75	0.03	83.95	2.09	3.09
ISA31	0.00	14.98	0.03	0.25	8.48	71.97	4.28
ISA32	0.00	11.55	1.25	0.00	77.57	0.18	9.46
ISA33	0.00	27.53	0.10	0.01	3.86	60.80	7.70
ISA34	0.00	18.26	0.00	0.20	2.98	74.53	4.03
ISA35	0.00	21.86	0.39	0.02	2.45	67.14	8.14
ISA36	0.00	41.95	0.00	0.05	4.06	50.31	3.62
ISA37	0.09	12.89	0.00	0.03	0.65	78.63	7.70
ISA38	0.00	40.37	0.10	0.01	0.70	56.45	2.38
ISA39	12.79	12.23	0.18	0.17	1.97	68.58	4.08
ISA40	0.00	24.17	0.00	0.02	2.47	68.30	5.05

Table 4-4. Continued

ISAs	% Clouds	% Forest	% Water	% Plantation	% Rice	% Upland Crops	% Built-up
ISA41	0.00	12.98	0.02	0.00	0.28	82.81	3.91
ISA42	0.00	4.24	4.55	0.00	86.37	0.06	4.78
ISA43	0.00	15.73	0.00	0.00	6.89	74.55	2.83
ISA44	0.00	12.62	0.02	0.06	3.17	79.56	4.56
ISA45	0.00	4.13	0.16	0.00	89.00	1.33	5.38
ISA46	0.00	37.34	0.35	0.06	1.45	56.84	3.96
ISA47	0.00	6.58	0.04	0.19	4.28	83.87	5.05
ISA48	0.00	10.96	0.02	0.00	1.09	84.68	3.25
ISA49	0.00	70.13	0.40	0.16	0.03	27.91	1.36
ISA50	0.00	63.61	0.23	0.23	2.20	32.30	1.42
ISA51	0.00	37.28	0.32	0.09	0.22	60.43	1.66
ISA52	0.00	24.76	0.00	0.07	1.60	70.55	3.03
ISA53	0.00	19.10	0.04	0.00	5.18	73.52	2.17
ISA54	0.00	25.78	0.00	0.11	3.06	67.76	3.28
ISA55	6.70	28.54	0.00	0.12	0.71	60.27	3.67
ISA56	0.00	19.58	0.34	0.00	6.66	66.70	6.72

Table 4-5. Land-Cover Distribution (in Percentage), 2006

ISAs	% Clouds	% Forest	% Water	% Plantation	% Rice	% Upland Crops	% Built-up
Entire Province	3.41	17.31	2.45	0.16	16.12	54.92	5.64
ISA01	0.00	1.18	0.97	0.01	92.88	0.61	4.36
ISA02	20.77	12.97	2.08	0.02	61.82	0.85	1.50
ISA03	28.33	5.60	0.27	0.02	60.86	1.51	3.42
ISA04	2.29	7.54	1.35	0.05	74.19	1.83	12.73
ISA05	0.45	6.28	0.65	0.02	67.34	8.94	16.32
ISA06	2.75	40.57	1.78	0.07	1.15	51.07	2.61
ISA07	0.03	6.96	0.05	0.12	4.56	78.07	10.23
ISA08	0.46	31.84	0.00	0.16	17.40	46.33	3.81
ISA09	11.71	3.88	0.01	0.01	6.54	70.34	7.50
ISA10	4.03	0.69	0.05	0.12	0.14	86.92	8.05
ISA11	33.65	2.54	0.01	0.00	1.28	58.88	3.64
ISA12	0.28	34.71	0.00	0.06	0.00	60.92	4.03
ISA13	7.90	1.46	0.05	0.05	0.22	80.00	10.32
ISA14	0.00	53.91	0.61	0.08	2.81	39.70	2.89
ISA15	0.00	34.57	0.04	0.36	1.65	61.07	2.30
ISA16	0.00	58.90	0.49	0.11	0.00	38.70	1.81
ISA17	0.00	6.93	0.89	0.52	2.71	79.63	9.32
ISA18	0.11	6.66	0.15	0.24	3.16	81.78	7.91
ISA19	0.00	22.15	0.00	0.20	0.65	72.33	4.66
ISA20	0.73	2.51	49.38	0.03	2.56	39.87	4.92
ISA21	0.04	7.91	1.42	0.45	2.92	73.86	13.40
ISA22	0.00	20.25	3.29	0.76	4.05	63.44	8.20
ISA23	1.69	2.52	0.00	0.08	0.84	85.53	9.35
ISA24	1.69	36.96	0.07	0.01	4.36	52.42	4.49
ISA25	0.00	3.59	0.76	0.00	1.80	88.47	5.38
ISA26	0.00	6.99	0.04	0.32	3.95	82.96	5.74
ISA27	0.00	1.54	0.00	0.02	2.45	90.45	5.54
ISA28	0.68	4.65	0.23	0.06	0.31	87.55	6.51
ISA29	0.00	4.95	0.05	0.01	82.62	4.59	7.78
ISA30	0.00	7.21	0.38	0.02	83.79	4.87	3.73
ISA31	0.00	10.07	0.00	2.00	1.95	79.58	6.40
ISA32	0.00	14.46	1.83	0.04	71.91	1.00	10.75
ISA33	0.00	7.46	0.11	0.02	0.61	84.86	6.94
ISA34	0.00	1.74	0.03	0.78	1.56	90.13	5.76
ISA35	0.00	3.58	0.46	0.16	1.17	88.30	6.32
ISA36	0.00	38.52	0.09	0.08	1.19	55.79	4.33
ISA37	0.09	14.33	0.01	0.01	0.96	78.08	6.53
ISA38	0.00	45.23	0.07	0.05	0.00	50.08	4.57
ISA39	12.79	10.40	0.06	0.07	0.05	70.19	6.44
ISA40	0.00	7.28	0.14	0.06	1.48	84.18	6.87

Table 4-5. Continued

ISAs	% Clouds	% Forest	% Water	% Plantation	% Rice	% Upland Crops	% Built-up
ISA41	0.00	10.36	1.34	0.10	1.90	80.71	5.60
ISA42	0.00	8.10	4.51	0.04	81.15	0.71	5.48
ISA43	0.00	11.10	0.00	0.05	5.29	79.68	3.89
ISA44	0.00	2.63	0.02	0.02	2.43	88.33	6.56
ISA45	0.00	7.71	0.59	0.00	82.54	1.84	7.32
ISA46	0.00	49.06	0.56	0.41	1.36	43.91	4.69
ISA47	0.00	0.69	0.05	0.26	1.00	91.14	6.87
ISA48	0.00	13.54	0.02	0.08	0.62	79.41	6.33
ISA49	0.00	40.03	0.23	0.37	0.06	53.14	6.17
ISA50	0.00	39.37	0.34	0.30	3.06	53.54	3.39
ISA51	0.00	8.74	6.90	0.02	0.06	78.59	5.69
ISA52	0.00	28.65	0.14	0.20	0.35	65.48	5.18
ISA53	0.00	12.37	2.22	0.34	0.94	80.02	4.11
ISA54	0.00	1.21	0.00	0.33	2.68	90.34	5.45
ISA55	6.70	1.79	0.00	0.16	1.27	84.31	5.77
ISA56	0.00	9.41	2.21	0.09	1.39	80.59	6.31

Table 4-6. Kendall's Tau (T) Test for Correlations among all ISAs (1-56).

Change of Indices	Change in % land cover											
	Forest		Water		Plantation		Rice		Upland Crops		Built-up	
	T- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.
α 1989-1998	-0.221	*0.012	0.074	0.225	0.053	0.298	-0.039	0.344	0.198	*0.021	0.424	*0.000
α 1998-2006	-0.123	0.111	-0.014	0.443	0.054	0.295	0.054	0.295	0.133	0.094	0.056	0.289
β 1989-1998	-0.258	*0.004	0.037	0.351	0.067	0.250	-0.093	0.169	0.255	*0.004	0.357	*0.000
β 1998-2006	-0.139	0.083	-0.013	0.447	0.036	0.359	0.033	0.371	0.147	0.072	0.082	0.207
γ 1989-1998	-0.154	0.058	0.063	0.259	0.106	0.145	0.051	0.300	0.153	0.060	0.365	*0.000
γ 1998-2006	-0.051	0.300	0.096	0.165	0.146	0.069	-0.129	0.095	0.080	0.208	-0.096	0.164

* = Significant at p-value < 0.05.
* * = Significant at p-value < 0.10.

Table 4-7. Kendall's Tau (T) Test for Correlations among Group 2 (ISAs 17-32), which the indices change in both 1989-1998 and 1998-2006

Change of Indices	Change in % land cover											
	Forest		Water		Plantation		Rice		Upland Crops		Built-up	
	T- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.	*T*- Test	Sig.
α 1989-1998	-0.083	0.326	-0.034	0.428	0.243	**0.096	0.267	**0.075	-0.050	0.394	0.333	*0.036
α 1998-2006	0.167	0.184	-0.343	*0.032	-0.133	0.236	0.117	0.264	-0.117	0.264	-0.200	0.140
β 1989-1998	-0.283	**0.063	-0.134	0.235	0.192	0.150	0.100	0.295	0.150	0.209	0.067	0.359
β 1998-2006	0.183	0.161	-0.427	*0.011	-0.117	0.264	0.100	0.295	-0.033	0.429	-0.117	0.264
γ 1989-1998	-0.086	0.328	-0.144	0.228	0.257	**0.091	0.200	0.149	0.010	0.480	0.257	**0.091
γ 1998-2006	0.150	0.209	-0.326	*0.039	-0.150	0.209	0.133	0.236	-0.133	0.236	-0.183	0.161

* = Significant at p-value < 0.05.
* * = Significant at p-value < 0.10.

Table 4-8. Kendall's Tau (T) Test for Correlations among Group 3 (ISAs 33-48), which the indices change in 1989-1998, but not in 1998-2006

	Change in % land cover											
Change of Indices	Forest *T*- Test	Sig.	Water *T*- Test	Sig.	Plantation *T*- Test	Sig.	Rice *T*- Test	Sig.	Upland Crops *T*- Test	Sig.	Built-up *T*- Test	Sig.
α 1989-1998	-0.117	0.264	0.133	0.236	0.188	0.159	-0.050	0.394	0.100	*0.050	0.467	*0.006
α 1998-2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
β 1989-1998	-0.150	0.209	0.100	0.295	0.205	0.138	-0.083	0.326	0.133	0.236	0.433	*0.010
β 1998-2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
γ 1989-1998	-0.100	0.295	0.117	0.264	0.239	0.102	-0.100	0.295	0.083	0.326	0.450	*0.008
γ 1998-2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* = Significant at p-value < 0.05.
* * = Significant at p-value < 0.10.

Table 4-9. Kendall's Tau (T) Test for Correlations among Group 4 (ISAs 49-56), which the indices change in 1998-2006, but not in 1989-1998

	Change in % land cover											
Change of Indices	Forest *T*- Test	Sig.	Water *T*- Test	Sig.	Plantation *T*- Test	Sig.	Rice *T*- Test	Sig.	Upland Crops *T*- Test	Sig.	Built-up *T*- Test	Sig.
α 1989-1998	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
α 1998-2006	-0.071	0.402	-0.546	*0.031	0.143	0.310	0.429	**0.069	0.286	0.161	0.357	0.108
β 1989-1998	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
β 1998-2006	-0.143	0.310	-0.473	**0.053	0.071	0.402	0.500	*0.042	0.357	0.108	0.429	**0.069
γ 1989-1998	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
γ 1998-2006	-0.036	0.450	-0.593	*0.022	0.182	0.267	0.400	**0.085	0.255	0.191	0.327	0.131

* = Significant at p-value < 0.05.
* * = Significant at p-value < 0.10.

Table 4-10. Wilcoxon Matched Pair Test for control group (Group 1)

Paired	Wilcoxon Z	Sig.
Forest 1998 - Forest 1989	-0.879	.379
Forest 2006 - Forest 1998*	-3.516	.000
Water 1998 - Water 1989	-0.414	.679
Water 2006 - Water 1998	-0.672	.501
Plantation 1998 - Plantation 1989*	-2.936	.003
Plantation 2006 - Plantation 1998	-1.086	.277
Rice 1998 - Rice 1989	-1.655	.098
Rice 2006 - Rice 1998	-0.362	.717
Upland Crops 1998 - Upland Crops 1989	-1.344	.179
Upland Crops 2006 - Upland Crops 1998*	-3.516	.000
Built-Up 1998 - Built-Up 1989	-1.603	.109
Built-Up 2006 - Built-Up 1998*	-2.223	.026

* = Significant at p-value < 0.05.

Table 4-11. Wilcoxon Matched Pair Test for non-control group (Groups 2, 3, and 4)

Paired	Wilcoxon Z	Sig.
Forest 1998 - Forest 1989*	-4.656	.000
Forest 2006 - Forest 1998*	-4.143	.000
Water 1998 - Water 1989	-1.718	.086
Water 2006 - Water 1998*	-2.352	.019
Plantation 1998 - Plantation 1989*	-4.541	.000
Plantation 2006 - Plantation 1998*	-3.214	.001
Rice 1998 - Rice 1989*	-3.927	.000
Rice 2006 - Rice 1998*	-2.743	.006
Upland Crops 1998 - Upland Crops 1989*	-4.675	.000
Upland Crops 2006 - Upland Crops 1998*	-3.457	.001
Built-Up 1998 - Built-Up 1989*	-4.750	.000
Built-Up 2006 - Built-Up 1998*	-3.771	.000

* = Significant at p-value < 0.05.

CHAPTER 5
SUMMARY AND CONCLUSIONS

This dissertation aims to develop a better understanding the inter-relationships between road network development (human actions) and land-cover (environment) as part of the broader realm of human-environment interactions. The overarching research question is how do roads interact with, or influence choices of, land covers and what are the specific drivers of land-cover changes in Lop Buri province?

Statistical measures of networks and their connectivity are employed to develop an understanding of how road network in Lop Buri province have changed over the two time periods, 1989-1998 and 1998-2006. Remote sensing techniques yield a land cover classification with 83% accuracy (2006 image), and land cover trajectories that can both be examined with relation to distance to the nearest roads. Logistic regression analysis identifies the principal drivers of land cover change within the province, while network analyses based on concepts of developed in graph theory are utilized to investigate how road connectivity and land cover dynamics are linked. In addressing the basic research question, various theories, tools and techniques, include graph theory, land cover classification/trajectories, GIS, remote sensing, spatial statistics and spatial modeling contribute to the formulation of a greater understanding of this important set of dynamic interaction.

The road network of Lop Buri province has expanded between 1989 -2006, but more noticeably so during the earlier period, 1989-1998. Development in latter period was slowed by the Asian economic crisis. Forest cover has decreased markedly over the last two decades and has principally been converted to upland crops in response to the demand for export to the overseas animal feeds industry and the government's agricultural diversification policies. Built-up areas have increased rapidly, particularly, along the road network. All of these land-cover change activities are found to occur with 6 km of roads. Higher percentages of land-cover trajectories (particularly from forest to upland crops) are found during in the earlier period, mirroring the degree of road network development, thereby suggesting a link between the two.

The road connectivity indices, alpha, beta, and gamma, are used to examine relationships between the road network development and land-cover dynamics in the context of whether the nature of the road system itself, rather than simply distance-to-road measures have an impact upon the type of land-cover change. Despite the increase in total length of roads over the study period, the connectivity indices showed no great change when viewed at an aggregate provincial scale, as developments were expansions into hinterland rather than any further linking existing roads. However, in those regions within the province where there were changes in road connectivity, strong positive relationships were identified with both higher percentages of upland crops and percentages of built-up areas present. As a corollary, forest cover declined with increased road network connectivity. Thus, in those areas that did experience road network development analysis showed greater connectivity, forest cover decline, and upland crops and built-up areas increased.

Since land-cover change can arise from numerous factors arranged in various combinations (Geist & Lambin, 2002), roads might not be the only contributors to the observed patterns in Lop Buri province. Slope, distance to forest edge, distance to towns, and high population density are significantly associated to forest loss and increase in upland crop cultivated areas.

Contributions Made by This Dissertation

The investigation of relationships between road network development and land-cover utilizing this multi-disciplinary approach enhances knowledge in two major related fields of study of particular importance in light of continued population growth and the emergence of developing nations of: human-environmental interactions and transportation geography. The implications of changes in land cover range as widely as global agriculture, global economies, biodiversity and global climate change. Increased understanding of the potential ramifications of decisions to expand road networks, and more specifically the changes in network characteristics, is a necessary prerequisite for correct planning and government policies in the future. Employing an array of theories, methods, and tools such as GIS, remote sensing, and spatial statistics (through development of statistical models), the study has contributed to a better understanding of human-environment interactions in the particular arena of land-use land-cover change (LUCC). Although Lop Buri province was chosen as a case study to the relationships between the road network development and land-cover change because of its long history of road development as well as rapid changes in land cover, many of the broader conclusions and techniques have application to many developing nations and to the field of LUCC.

Graph theory provides the theoretical framework upon which a more comprehensive understanding of the relationship between the properties of the road network itself (not merely distance to roads) and land-cover dynamics may be based. Several studies have attempted to use a map-based approach through distance to roads measures; however, they lack the ability to represent or consider the implications of what the nearby road networks offer in terms of broader connection to the region, nation or world. This research attempts to numerically and objectively incorporate such considerations into the development of models of land-cover dynamics.

The majority of existing studies of the role of expanding road networks in regions of tropical forest have concentrated on the Amazon (e.g., Pfaff (1999), Arima, et al. (2005) and Laurance, et al (2002)) while little attention has been paid to the losses of forest in tropical Asia. The example of Lop Buri province more closely exemplifies the prevailing conditions in the agriculturally-based provinces of Thailand and other tropical Asian countries. Results of the study provide insights for decision-making in regional and economic development and in transportation planning in balancing socio-economic economic development as well as enhance the environmental integrity.

Limitation of the Study and Future Research

Other environmental impacts associated with road network development such as air pollution, noise pollution, chemical runoffs, or habitats loss, and their social and economic impacts are not examined, focusing more on the impacts of the connectivity that the expanding road network might provide at various geographic scales (local, provincial, national, international) . The latter focus was achieved through the extensive application of geospatial data, tools and techniques including satellite images, GIS layers, and spatial modeling. Data availability, data consistency, and study area delineation provide some limitations both in terms of this study and other potential applications in the developing world. Satellite imagery, and therefore the temporal increment of the study were limited to certain dates due to the budget constraints. The images only provide “snap-shots” of the manifestation of the continuous and dynamic processes of land-cover change over each 7-8 years period. Thus, processes and changes operating within shorter time periods may elude this study.

All conclusions concerning land-cover change are predicated upon the land cover classification which was approximately 83% accurate (based on 2006 Landsat image); hence, there is about 17% margin of classification errors. This could be reduced with the collection of more training samples, especially for those classes that have now been identified as having low accuracy (e.g. plantation and rice). As the road data were compiled from several different agencies, some inconsistencies exist. One major draw-back is the absence of the metadata from these agencies describing the quality of the data. GIS digitizing is a new advanced technology to Thailand, thus there are few safeguards for agencies to ensure the data validation. Processes to ensure consistency and increase the accuracy of the road layer were carried out by using auxiliary data including; using topographic maps and satellite images for line consistency, and topology correction to eliminate data duplication.

The study area was delineated on the basis of political boundaries, thus, roads extending beyond this arbitrary limit to other regions and major cities in Thailand were omitted. Given the national nature of the road network, it was difficult to determine where roads should end or how to delineate the study area boundary, even when this impact was mitigated by extending the road network by 6 km beyond the Lop Buri province political boundary line. Similarly, the intensive study areas (ISAs) are defined by arbitrary bounds based on the random sampling points. Thus, network indices in terms of the numbers of nodes and links were limited within these boundary lines. This further raises the questions of the scale at which roads were connected, and, in the strictest sense, limits the geographic scale of the conclusions of this work to the local and provincial level. However it does not limit the applicability of the methods themselves.

The variables used in logistic regression were primarily limited to readily available biophysical data. In the future, it is recommended that additional socio-economic data be incorporated in order to capture more of the “human” drivers in the human-environment interactions that might come into play in land-cover dynamics.

Despite these limitations, this research establishes an initial understanding of the relationships between road network development and land-cover, understanding the processes of LUCC and its drivers in Lop Buri province. It also establishes a theoretical and technical framework for the determination of the impacts of changes in road networks and land covers in developing nations. This framework has the flexibility to be modified depending upon local conditions, availability of data and the geographic scale at which the conclusions will ultimately be applied.

Future Directions

This dissertation has shown a link between road network development, which aimed for economic development, and land-cover change in Lop Buri province. To further investigate the relationships of the road network development on land-cover; firstly, other characteristics of the road network should be incorporated. These include road types (paved vs. unpaved, highway vs. local, and 1-lane vs. 4-lane), speed limited, and road width. This sets a basis in a comparison between types of road and land-cover. Next, it would be useful to analyze these road networks separately; for example, determining network connectivity among the highways and connectivity among local roads. Lastly, other social-economic variables (e.g., education, income, and land tenure) could be used in the logistic regression model. Incorporating these socio-economic variables would better assess other drivers of land-cover change. These future directions would be contributed to the knowledge of human-environmental relationship community.

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BIOGRAPHICAL SKETCH

Risa Patarasuk was born in Bangkok, Thailand where she lived until the age of fifteen. She attended high school in the United States and Australia, and received her undergraduate degree in environment planning from the University of Hawkesbury in Sydney. She earned a Master of Science degree in environmental and natural resource economics from Chulalongkorn University in Bangkok, Thailand and Master of Arts in urban planning from the University of Akron in Ohio. While attending the University of Akron, she completed several internships including one at The National Geographic Society in Washington, D.C. and two with the National Parks Service, also in Washington.

As a Ph.D. student at the University of Florida, she specialized in human-environmental interactions, land-use and land-cover change, road network analysis, GIS and remote sensing. While at the University of Florida, she taught several undergraduate classes including ‘Geography for the Changing World’, ‘Physical Geography’, and a ‘Physical Geography Lab.’ She received her Ph.D. in Geography with a minor in geo-spatial technology from the University of Florida in the Fall of 2011.